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**Heat Stress in Urban Environments:
A Case Study of Heat Vulnerability in New Haven, CT**

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Environmental Studies (BS, Urban Environments) Thesis
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Abstract

A place-based understanding of heat and its behavior is necessary for appropriately preparing our cities and protecting the most vulnerable populations from this urgent climate and public health threat. This paper aims to identify the areas in New Haven, CT that have the highest autumnal temperature exposure and sensitivity to provide evidence for developing mitigation and adaptation measures. Original temperature data was collected using a bike-mounted Smart T sensor and then compared with data on land cover and water proximity. These heat exposure estimates were analyzed with 2019 Census data on age, income, race, and ethnicity, for 19 census tracts within 5 major neighborhoods. It was expected that heat distribution in New Haven would be concentrated in areas with less tree cover and less water proximity, as well as areas with high income and race sensitivity. The warmest neighborhood in the city was The Hill, closely followed by Dixwell. The Hill had low tree cover and higher heat exposure in the areas away from the water, as expected. Despite a positive relationship between both income and race with temperature ($r_s = .34$ and $r_s = .41$, respectively), it was not statistically significant—most likely due to seasonality and data set size. Further investigation of New Haven's urban heat landscape in the summer months and at a larger scale is needed to fully understand heat vulnerability and to improve heat mitigation and adaptation measures.

Introduction

The anthropogenic changes to the climate of our planet are not just complex in how they were created, but also in how they will be felt. Climate change projections anticipate a wrath of more extreme storms, floods, sea level changes, seasonal patterns, and heat in the near future.¹ For many, however, these changes are quickly becoming reality. This transformation is most clearly seen in the annual rise in temperature, with widespread average increases being recorded regularly and extreme heat days increasing in frequency every year.² These figures are alarming given the lethal potential of heat stress: an increase of just 1°F of heat intensity can increase mortality risk by 2.5%.³ Adding to the complexity and significance of rising temperatures, this public health threat disproportionately impacts vulnerable demographic groups.⁴ While severe, one-time weather events are less predictable, consistent changes in local climates are inevitable and preparing for the reality of a warmer future is tremendously important.

The environmental composition of dense urban areas— namely the quantity of large structures, concrete coverage, and lack of greenspace—differs greatly from non-urban or rural areas, which results in warmer temperatures compared to their surroundings and is called the urban heat island (UHI) effect.⁵ The heat-absorbing surfaces and structures that contribute to the UHI effect are distributed unevenly within a city. This distribution is subject to the unique

¹ Cecily J. Maller and Yolande Strengers. "Housing, heat stress and health in a changing climate: promoting the adaptive capacity of vulnerable households, a suggested way forward." *Health promotion international* 26, no. 4 (2011): 492-498.

² David C. Reidmiller et al. "Fourth national climate assessment." *Volume II: Impacts, Risks, and Adaptation in the United States, Report-in-Brief* (2017).

³ G. Brooke Anderson and Michelle L. Bell. "Heat waves in the United States: mortality risk during heat waves and effect modification by heat wave characteristics in 43 US communities." *Environmental health perspectives* 119, no. 2 (2011): 210-218.

⁴ R. Sari Kovats and Shakoor Hajat. "Heat stress and public health: a critical review." *Annu. Rev. Public Health* 29 (2008): 41-55.

⁵ Katrina Proust et al. "Human health and climate change: leverage points for adaptation in urban environments." *International journal of environmental research and public health* 9, no. 6 (2012): 2134-2158.

biophysical attributes of the landscape and is therefore different for every city. Heat is a place-based issue that necessitates an understanding of its behavior in our present reality, in order to mitigate the public health and climate dangers of our approaching future.⁶ Breaking down heat stress into two components, exposure and sensitivity, offers a framework for understanding how temperatures behave in a city and who they threaten.⁷

URBAN HEAT ISLAND (UHI) EFFECT:

THE TEMPERATURE DIFFERENCE BETWEEN URBAN AREAS AND THEIR SURROUNDINGS AS A RESULT OF THEIR UNIQUE ENVIRONMENTAL COMPOSITION.

To understand how the UHI effect varies across New Haven and to identify the parts of the city that experience the most heat exposure, I present estimates of temperature distribution based on data collected using a bike-mounted Smart T sensor. I calculate anomalies from the average recorded

temperature of the city to account for the UHI effect and compare data collected over varying temporal periods. To identify the warmest parts of the city, I highlight temperature variations within each neighborhood and analyze the differences across the five areas. The results of the temperature collection are compared with tree cover, impervious surface distribution, and proximity to water to understand the factors potentially contributing to the variation. This establishes the exposure component of my heat stress analysis.

Next, I evaluate data about four key social factors that influence heat stress sensitivity for each of the major neighborhoods. The four sensitivity factors include the proportion of the population that is low income, at-risk age, and belonging to a racial or ethnic minority. This data helps determine the people and parts of the city that are already subject to economic, social, or environmental obstacles. These obstacles are largely rooted in systemic inequity and are likely

⁶ Jeremy J. Hess, Josephine N. Malilay, and Alan J. Parkinson. "Climate change: the importance of place." *American journal of preventive medicine* 35, no. 5 (2008): 468-478.

⁷ Claus Rinner et al. "The role of maps in neighborhood-level heat vulnerability assessment for the city of Toronto." *Cartography and Geographic Information Science* 37, no. 1 (2010): 31-44.

to cause these New Haven residents to suffer the worst consequences of increased heat stress. Finally, the exposure and sensitivity components are compared in order to assess overall vulnerability and identify those most at risk of suffering heat-related health issues. Ultimately, this analysis will contribute to an understanding of how New Haven will feel the impacts of the changing climate.

Consistent with other literature, I expect that the distribution of heat in New Haven will be concentrated in areas with less tree cover and more distance from bodies of water. More specifically, I anticipate areas with these biophysical features will experience more heat exposure, which will be shown in positive temperature anomalies from the mean temperature of the city. In turn, I expect this exposure to be concentrated in neighborhoods with predominantly-minority and low-income residents—meaning areas with more sensitivity—since their homes are more likely to be surrounded by poor environmental characteristics. This will identify the people and parts of the city that have the highest temperature exposure and heat sensitivity, therefore requiring the most preparation for the warming climate, and provide evidence for developing mitigation and adaptation measures.

Background

Heat and Health

Heat is recognized as a public health concern, rather than a mere health risk, in part because of its disproportionate impacts on already vulnerable populations. Several established social determinants of health that have a role in shaping extreme heat outcomes include age, income, race, and ethnicity. Age groups most vulnerable to heat-related illness (HRI) and death include infants and the elderly (65 yrs or older), due to their susceptibility to heat stroke and a combination of lifestyle factors that make them more likely to be living in unfavorable conditions.⁸ Individuals living in an area experiencing the UHI effect within these age groups are even more at risk because of the higher heat indices.⁹ Other demographic factors, like income, can indicate a higher likelihood of heat sensitivity in urban areas. In Toronto, 9-1-1 calls were found to peak earlier than some heat health warning systems, with spatial data of these calls revealing that low-income neighborhoods were among those experiencing higher rates of HRI.¹⁰ In Phoenix, AZ researchers found that wealthy white people were more likely to live in areas with lots of vegetation and less climate stress.¹¹ Another study found that racial- and ethnic-minority groups have a higher heat susceptibility in the United States because of socioeconomic disparities, living conditions, occupational exposure, and language barriers.¹² In an evaluation of urban heat management strategies compared with the risk assessments of climate projections,

⁸ Barbara K. Bailes and Kathleen Reeve. "Prevention of Heat-Related Illness." *The Journal for Nurse Practitioners* 3, no. 3 (March 2007): 161–68. <https://doi.org/10.1016/j.nurpra.2006.12.001>.

⁹ Bailes and Reeve. "Prevention of heat-related illness."

¹⁰ Kate L. Bassil et al. "Temporal and spatial variation of heat-related illness using 911 medical dispatch data." *Environmental research* 109, no. 5 (2009): 600-606.

¹¹ Sharon L. Harlan et al. "In the shade of affluence: the inequitable distribution of the urban heat island." In *Equity and the Environment*. Emerald Group Publishing Limited, 2007.

¹² Alana Hansen et al. "Vulnerability to extreme heat and climate change: is ethnicity a factor?." *Global health action* 6, no. 1 (2013): 21364.

it was concluded that areas with vulnerability in age, income, and race must be prioritized to be “most protective of human health.”¹³

Climate Change in the Northeast

Despite having cooler annual temperatures than many other parts of the country, the Northeast is not safe from the detrimental effects of high heat intensity. This region of the country has one of the largest numbers of HRI incidents and deaths due to poor adaptations to extended extreme heat exposure.¹⁴ Many people in the Northeast do not have air conditioning and their bodies have not undergone acclimation that would otherwise help them endure such conditions.¹⁵ While it's clear that extreme heat is among the most dangerous and lethal weather events, it's important to note that these negative health outcomes will only be exacerbated by the impacts of our changing climate. Under the best-case scenario for emissions and with the most ambitious predicted climate response (RCP 4.5), the Northeast is predicted to see a 3.98°F increase in annual average temperatures by Mid-Century.¹⁶ The more alarming predicted increase with a high emissions and low climate-response scenario (RCP 8.5) is 5.09°F by Mid-Century.¹⁷ Studies have projected that, in addition to increases in average temperatures by the end of this century, there will be an approximate doubling or tripling of the number of hot days each summer.¹⁸ Under either scenario, an increase of 650 premature deaths per year is predicted by 2050 and between 960 to 2,300 additional premature deaths per year by the end of

¹³ Jason Vargo et al. "The social and spatial distribution of temperature-related health impacts from urban heat island reduction policies." *Environmental Science & Policy* 66 (2016): 366-374.

¹⁴ Bailes and Reeve. "Prevention of heat-related illness."

¹⁵ Bailes and Reeve. "Prevention of heat-related illness."

¹⁶ Donald J. Wuebbles, David W. Fahey, and Kathy A. Hibbard. "Climate science special report: fourth national climate assessment, volume I." (2017).

¹⁷ Wuebbles, Fahey, and Hibbard. "Climate science special report: fourth national climate assessment, volume I."

¹⁸ Katharine Hayhoe et al. "Regional climate change projections for the Northeast USA." *Mitigation and Adaptation Strategies for Global Change* 13, no. 5-6 (2008): 425-436.; Radley M. Horton et al. "Climate hazard assessment for stakeholder adaptation planning in New York City." *Journal of Applied Meteorology and Climatology* 50, no. 11 (2011): 2247-2266.

the century.¹⁹ For Connecticut specifically, a low emissions scenario predicts its coldest years being 3°F warmer than the long-term average, whereas a high emissions scenario is predicted to have its hottest years 10°F over the warmest year in the historical record.²⁰ Already, we are seeing a trend of more warm nights in Connecticut, which minimizes opportunities for individuals to recover from intense daytime temperatures.²¹

On an urban scale this is significant because temperatures can vary tremendously over their small area, which subjects urban areas and populations to different levels of heat exposure and heat-related health outcomes. A study of heat-related mortality in the urban Northeast, including Philadelphia, New York, and Boston, found that despite Philadelphia having the hottest temperatures overall, New York had the highest mortality.²² This was attributed to the impacts of the UHI effect and demographic variables, such as access to air conditioning, age, and pre-existing conditions. This demonstrates that the health effects of intra-urban temperature distribution are significantly influenced by the presence of the UHI effect, as well as social factors that can determine the resilience of individuals exposed to heat.²³ Climate change is only adding to the urgency and severity of the heat and health relationship.

The Urban Heat Island Effect and Environmental Justice

Higher temperatures observed in urban areas, as a result of the UHI effect, is the most important aspect of place-based study of extreme heat.²⁴ In addition to the urban-rural discrepancy in warming, there is variation in temperature *within* cities. Environmental factors

¹⁹ Lesley-Ann L. Dupigny-Giroux et al. *Northeast*. US Global Change Research Program, 2018. Available at: <<https://pubs.er.usgs.gov/publication/70201872>>.

²⁰ Jennifer Runkle et al. 2017: Connecticut State Climate Summary. *NOAA Technical Report NESDIS 149-CT*, 4 pp. <https://statesummaries.ncics.org/ct>

²¹ Runkle et al. 2017: Connecticut State Climate Summary.

²² Elisaveta P. Petkova et al. "Projected heat-related mortality in the US urban northeast." *International journal of environmental research and public health* 10, no. 12 (2013): 6734-6747.

²³ Joyce Klein Rosenthal, Patrick L. Kinney, and Kristina B. Metzger. "Intra-urban vulnerability to heat-related mortality in New York City, 1997–2006." *Health & place* 30 (2014): 45-60.

²⁴ T. C. Chakraborty and Xuhui Lee. "A Global Database of Surface Urban Heat Island Intensity." (2019).

such as greenspace, density and composition of the built environment, and the presence of large bodies of water, all influence the intra-urban fluctuations. The presence of tree cover helps reduce temperatures in an area by providing shade and by removing heat from the air through evapotranspiration.²⁵ Similarly, bodies of water provide an evaporative cooling effect that can lower temperatures in a nearby area.²⁶ Alternatively, the solar reflectance, heat capacity, and thermal emissivity of many urban materials raise the temperature and help develop urban heat islands.²⁷ Land use and its changes have also been shown to be spatially correlated with UHI intensity.²⁸ Understanding the influence of these environmental components across a city helps to pinpoint the underlying factors contributing to cool pockets or hot spots (Figure 1). It is well established that land cover is correlated with land surface temperature spatially, so it is important to consider how this dynamic may be impacting the city of New Haven. Comparing tree cover and impervious surfaces to temperature in the exposure analysis will aid in developing a clear understanding of the physical environment's influence on heat inequities and highlight possible pathways to mitigating this exposure.

²⁵ Hashem Akbari et al. "Peak power and cooling energy savings of shade trees." *Energy and buildings* 25, no. 2 (1997): 139-148.

²⁶ Golnoosh Manteghi, Hasanuddin bin Limit, and Dilshan Remaz. "Water bodies an urban microclimate: A review." *Modern Applied Science* 9, no. 6 (2015): 1.

²⁷ US EPA. "Heat Island Compendium." (2014). <https://www.epa.gov/heatislands/heat-island-compendium>

²⁸ J. F. He et al. "Assessing the effect of land use/land cover change on the change of urban heat island intensity." *Theoretical and Applied Climatology* 90, no. 3-4 (2007): 217-226.

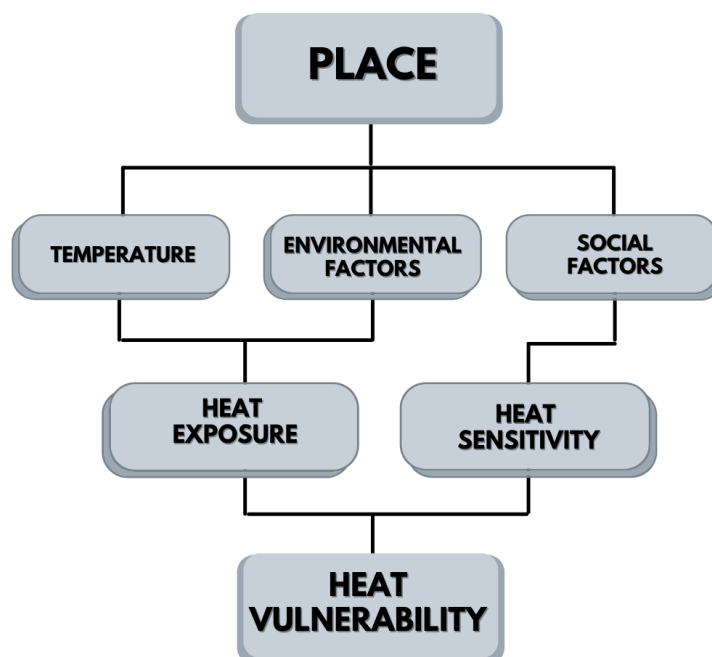


Figure 1. A framework for understanding the relationship between place and heat vulnerability and to show the path of this analysis.

In the same way that environmental factors are elements of place that influence heat distribution, social factors are elements of place that can determine heat sensitivity. As previously discussed, age and income are among the most clear social factors connected to either positive or negative heat-health outcomes. Neighborhoods in urban areas are often conglomerations of socioeconomically and racially similar people. As a result, issues that are geographically discriminatory, like heat, lend themselves to also affect certain demographic groups differently. This has been shown to be true in the case of extreme heat: low-income neighborhoods experience higher temperatures and neighborhoods that fell victim to racially discriminatory housing policies—known as redlining—also have higher heat exposure.²⁹⁻³⁰ On top of having fewer greenspaces and surfaces with higher heat capacity, low-income neighborhoods

²⁹ T. Chakraborty, A. Hsu, D. Many, and G. Sheriff. "Disproportionately higher exposure to urban heat in lower-income neighborhoods: a multi-city perspective." *Environmental Research Letters* 14, no. 10 (2019): 105003.

³⁰ Jeremy S. Hoffman, Vivek Shandas, and Nicholas Pendleton. "The effects of historical housing policies on resident exposure to intra-urban heat: A study of 108 US urban areas." *Climate* 8, no. 1 (2020): 12.

often have a large renter population. Since renting influences housing quality and the level of investment, this subsequently subjects people to housing conditions that are less equipped to provide heat refuge.³¹ In addition, lower income individuals tend to have higher housing burdens, meaning they spend a larger portion of their income on housing costs, further compounding the factors that influence resilience in high heat situations.³²

Existing literature has shown that income, age, race and ethnicity are social factors linked to place and thus, heat-health outcomes. Given that the UHI effect causes an unequal distribution of heat, is influenced by the built environment, and negatively impacts already vulnerable populations, recognition of UHI intensity as an issue of environmental justice is crucial. The built environment can be altered and improved so that vulnerable populations are less vulnerable to the dangers of heat. By identifying heat sensitivity across New Haven through an analysis of indicating social factors, we can better understand how changes in heat exposure will impact the city's residents and take action to protect them.

³¹ K. Davilla, M. Abraham, and C. Seaberry. "Towards Health Equity in Connecticut: The Role of Social Inequality and the Impact of COVID-19." *Connecticut Connecticut Health Foundation* June (2020).

³² Davilla, Abraham, and Seaberry. "Towards Health Equity in Connecticut: The Role of Social Inequality and the Impact of COVID-19."

Energy Vulnerability

Place is a determinant of energy use and costs because of the geographic nature of laws, fuel prices, and climate. An individual's relationship to energy is largely dictated by the conditions of their housing-- the age, quality of the structure, whether they rent or own, central air conditioning versus units, etc. The energy burden of an individual, meaning the portion of their income that is spent on energy costs, combined with their level of energy insecurity help to characterize their overall relationship with energy. Energy relationships are an indicator of other social factors and can also be an obstacle to heat refuge and mitigation. There's a documented relationship between rising temperature and incidences of heat stress that are growing in severity due to climate change, therefore, issues related to energy access will continue to be exacerbated.³³

ENERGY BURDEN:

THE PERCENTAGE OF AN
INDIVIDUAL'S INCOME SPENT ON
ENERGY COSTS.

ENERGY INSECURITY:

THE TYPE AND QUALITY OF
HEATING AND COOLING ONE CAN
ACCESS.

An evaluation of residential energy use in Connecticut shows that despite energy prices being higher in this state—which otherwise might encourage more conservative energy use—energy consumption is above the national average.³⁴ This report also reveals that low-income households spend a larger portion of their income on energy costs than higher income groups, indicating inequitable energy burden trends. This data raises questions about the economic obstacles contributing to energy insecurity, socioeconomically disparate housing conditions

³³ Tomoko Hasegawa et al. "Quantifying the economic impact of changes in energy demand for space heating and cooling systems under varying climatic scenarios." *Palgrave Communications* 2, no. 1 (2016): 1-8.

³⁴ Booz Allen Hamilton Inc. Residential Energy Efficiency in Connecticut [PDF]. *Housing Development Fund*. (2012, March). Accessed via <https://hdfconnects.org/PDFs/StrategicSimulationBriefingBook.pdf>

that contribute to energy costs, and highlight a potential area of action in combating the negative effects of heat on health. Additionally, it points to ways that energy may be a compounding factor in the ability of low-income households to adapt to increased heat intensity. If low-income neighborhoods have higher heat exposure they are more vulnerable than a high-income neighborhood because they have fewer paths or resources for resilience against heat stress.

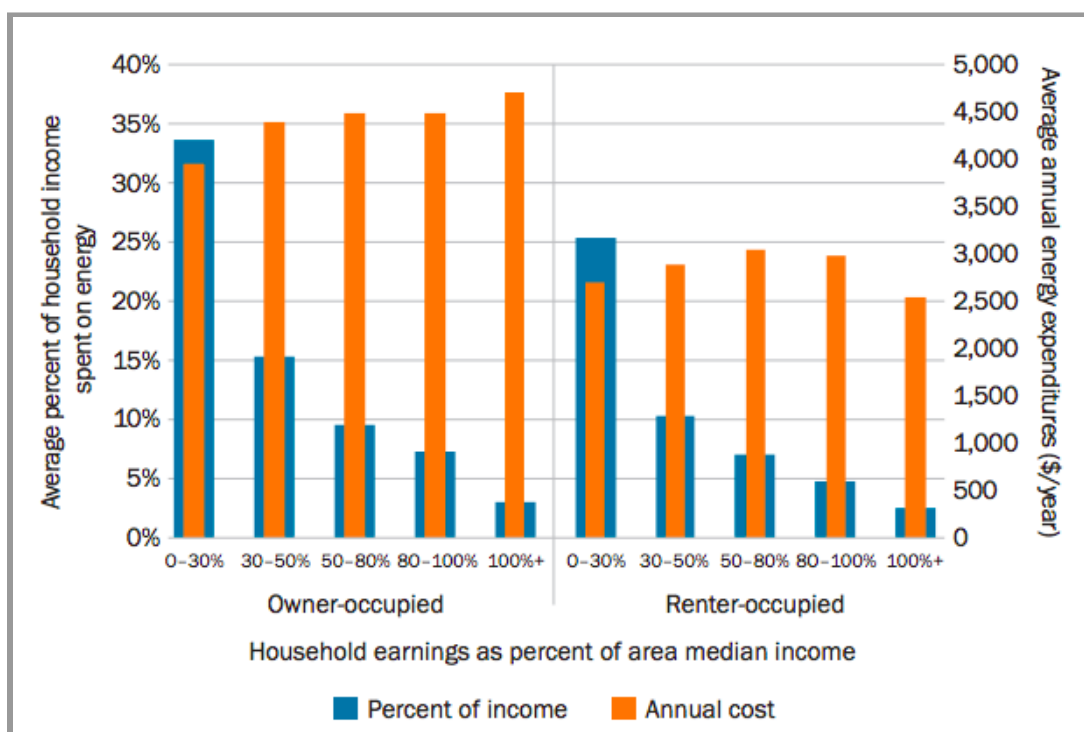


Figure 2. Average energy expenditures and energy burden for residential units (2015) in New Haven, Connecticut (Source: U.S. Census, U.S. Housing and Urban Development, and Energy Information Administration data³⁵).

Another report, from the Department of Energy, analyzes the unique relationship between low-income neighborhoods and energy use and costs in New Haven.³⁶ Their findings reflect the trends seen across the state— that low-income households pay a larger portion of their income

³⁵ Booz Allen Hamilton Inc. Residential Energy Efficiency in Connecticut.

³⁶ Office of Energy Efficiency and Renewable Energy. *New Haven, Connecticut: Targeting Low-Income Household Energy Savings*. U.S. Department of Energy. (2017, November). https://www.energy.gov/sites/prod/files/2018/02/f48/Cities-LEAP_Data%20to%20Decisions_New%20Haven%2C%20Connecticut_0.pdf

toward energy use than others. For both owner- or renter-occupied households, the energy burdens for those earning 80% or less of the area median income are significantly higher than 6%, the standard of affordability.³⁷ The lowest income group, making 0-30% of the area median income, suffers a 25% energy burden for renters and 34% for owner-occupied homes.

Energy is a factor that intersects with heat sensitivity and exposure through its positioning as a means for adapting to extreme heat and improving health outcomes. Energy also has the potential, however, to exacerbate negative health outcomes due to the nearly identical relationship between the social factors that make one vulnerable to heat and those that increase energy vulnerability. While energy data by household or neighborhood were inaccessible at the time of this research, the trends observed at the city level provide enough evidence that income is a strong indicator of energy vulnerability. Therefore, when evaluating heat vulnerability, energy must be recognized as a compounding factor of any income-related sensitivity.

³⁷ U.S. Department of Energy. *Targeting Low-Income Household Energy Savings*.

The City of New Haven: A Brief History

Early Racial Makeup

At the time the city was incorporated in 1784, around 30,000 people inhabited New Haven. By the turn of the twentieth century, however, the population more than tripled to 108,000.³⁸ With this growth, the city population was then roughly one third white, one third second generation Americans, one third immigrants, and three percent Black Americans.³⁹ Notably, the population of immigrants doubled in the last twenty years of the nineteenth century.⁴⁰ This influx of immigrants would have a lasting impact on the city, particularly in the formation of neighborhoods, community, and by changing the size of the city tremendously. To this day, the Wooster Square neighborhood is still known as a predominantly Italian area where many immigrants originally resided upon arriving in New Haven.

Between 1910 and 1940, the population in the city more than doubled, jumping from 133,000 to over 300,000.⁴¹ This population boom maintained the same majority-white racial makeup, with only three percent Black people and no significant amount of any other race. By 1960, however, the portion of Black city residents increased five fold while the total population changed by less than one percent.⁴² This drastic shift in the demographics of the city reflect the

³⁸ "1790 Census: Return of the Whole Number of Persons within the Several Districts of the United States." *U.S. Census Bureau* (U.S. Census Bureau, 1793.), <https://www.census.gov/library/publications/1793/dec/number-of-persons.html>.; "Twelfth Census of the United States Taken in the Year 1900, Population, Part 1. *U.S. Census* (U.S. Census Bureau, 1901.), <https://www.census.gov/library/publications/1901/dec/vol-01-population.html>

³⁹ "Racial Make-Up Of The Population: Major U.S. Cities, 1900." *U.S. Census* (U.S. Census Bureau, 1901.), Available at: http://www.library.yale.edu/thecitycourse/Census_PDFs/1900/Racial_make_up_of_US_cities_1900.pdf.

⁴⁰ "Statistics Of Population: Male And Female And Native And Foreign Born Population, By Counties." *U.S. Census* (U.S. Census Bureau, 1901.), Available at: http://www.library.yale.edu/thecitycourse/Census_PDFs/1900/Population_by_sex_and_foreign_and_native_born_CT_Counties_1880_1890_1900.pdf

⁴¹ "Potential Voting Population for the New Haven Metropolitan District." *U.S. Census* (U.S. Census, 1940.), Available at: https://newhavenhistory.library.yale.edu/Census_PDFs/1940/New_Haven_by_race_and_nativity_totals_1940.pdf

⁴² "General Characteristics of the Population, By Census Tracts." *U.S. Census* (U.S. Census, 1960.), Available at:

impact of suburbanization on New Haven as many affluent white residents left and large numbers of Black residents moved in from the South.⁴³ This trend continued over the following decades, leading to the Black population making up a third of people in the city today.⁴⁴

Suburbanization and Urban Renewal

As the world moved out of the Depression era and into the age of the New Deal, a critically important organization was developed and deployed into many cities in America: the Home Owners' Loan Corporation (HOLC).⁴⁵ Paid for and sponsored by the federal government, maps were drawn of city neighborhoods with designations according to their supposed investment risk level. In reality, however, these ratings of "best" to "declining" or "hazardous" were unjustly slighted to demarcate Black neighborhoods in red, indicating the highest level of risk to mortgage lenders.⁴⁶ These redlined maps are a significant institutional relic that created barriers for Black people to access credit lines or purchase homes for decades—with some areas still feeling the effects of this systematic racism today. In New Haven the HOLC redlined The Hill, Fairhaven, and Dixwell neighborhoods, which falls in accordance with the significant portion of people of color that live there today, as well as the large number of renter-occupied houses (Figure 3).

REDLINING:

THE TERM USED TO DESCRIBE THE GRADING OF BLACK NEIGHBORHOODS AS HIGH RISK FOR INVESTMENTS IN THE 1930S-40S. THEY RECEIVED A GRADE 'D' AND WERE COLORED RED ON THE HOLC MAPS.

https://newhavenhistory.library.yale.edu/Census_PDFs/1960/Characteristics_of_the_Population_by_census_tract_New_Haven_1960_Tracts_1_to_7_and_New_Haven_County.pdf

⁴³ "General Characteristics of the Population, By Census Tracts." U.S. Census. 1960.

⁴⁴ "QuickFacts: New Haven City, Connecticut." (2019). *Census Bureau QuickFacts*
<https://www.census.gov/quickfacts/newhavencityconnecticut>

⁴⁵ Nelson, Robert K. et al. "Mapping inequality: Redlining in New deal America." *American Panorama* (2018). <https://dsl.richmond.edu/panorama/redlining/#loc=5/39.1/-94.58>

⁴⁶ Brad Plumer and Nadja Popovich, "How Decades of Racist Housing Policy Left Neighborhoods Sweltering," *The New York Times*, August 24, 2020, sec. Climate,
<https://www.nytimes.com/interactive/2020/08/24/climate/racism-redlining-cities-global-warming.html>.

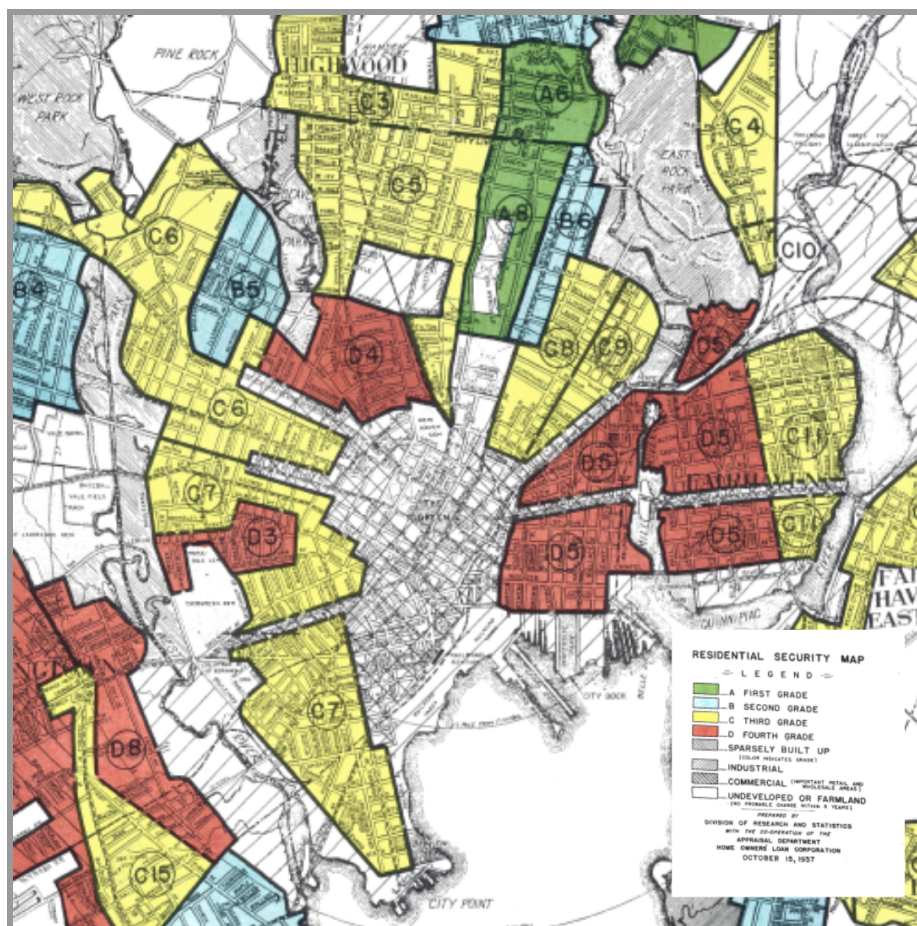


Figure 3. The map of New Haven produced by the Home Owners' Loan Corporation, with grade D areas colored in red.⁴⁷

A census report on the quality of housing in 1940 reveals that a majority of the houses falling into the “needing major repairs” category also happened to be in Census tracts within The Hill, Dixwell, or Fair Haven neighborhoods.⁴⁸ These conditions were ignored by local leaders until the city government adopted a devastating slum clearance strategy in the 1950s.⁴⁹ Led by Mayor Richard Lee, efforts to transform New Haven into a “slumless city” contributed to one of the most significant periods in the city’s history as homes and businesses were erased. To make

⁴⁷ Nelson et al. “Mapping inequality: Redlining in New Deal America.”

⁴⁸ “Quality of Housing by Census Tract: New Haven.” *U.S. Census* (U.S. Census, 1940.) Available at: https://newhavenhistory.library.yale.edu/Census_PDFs/1940/Quality_of_housing_by_tracts_New_Haven_1940.pdf

⁴⁹ Douglas W. Rae. “City: Urbanism and Its End.” *Yale University Press*, 2003. www.jstor.org/stable/j.ctt1np937.

matters worse, these projects were orchestrated and designed for the mayor by a team of developers, architects, and leadership from Yale, despite the clear conflict of interest.⁵⁰ After receiving an incredible \$180 million in federal funding for urban renewal and serving as the national poster child because of its many ambitious projects, New Haven is full of lessons to be learned. The low-income and predominantly Black Oak Street neighborhood was bulldozed so a highway— for connecting the city to the suburbs—could be built.⁵¹ The highway was ultimately never finished. Families displaced by this project—estimated to be as many as 8,000 people over 14 years—were promised relocation by the city.⁵² However, the city had no concrete plans in place to rehouse these citizens and many of them were moved multiple times as their new residences became the site of new renewal projects.⁵³

The city of New Haven's own government has made a considerable amount of mistakes in the development of the city over the past century. The destruction of neighborhoods— particularly those of people of color—contributed to the increase in commercial and industrial property, which is made of materials with high heat capacity and low evaporation potential. Moreover, the relocation that was forced upon these unhoused city residents moved them into areas with even less livable quality. The city that we see today is still marked by this past, as seen in the racial makeup, distribution of residents, and in the socio-economic divide of residents spatially. It is important to understand how heat may be compounding many of these social issues, especially if the distribution of heat exposure is found to be correlated with race or income.

⁵⁰ Rae. "City: Urbanism and Its End."

⁵¹ Mark Zaretsky, "75 years later, New Haven still reshaping 'urban renewal'." *New Haven Register*, September 29, 2018. Retrieved from <https://www.nhregister.com/news/article/75-years-later-New-Haven-still-reshaping-the-13266864.php>

⁵² Rae. "City: Urbanism and Its End."

⁵³ Lizabeth Cohen. *Saving America's Cities: Ed Logue and the Struggle to Renew Urban America in the Suburban Age*. (Farrar, Straus and Giroux, 2019.)

Yale's Footprint



Figure 4. a) A portion of an 1893 map of New Haven that shows Yale's campus at the time next to b) a view of the campus situated inside the larger downtown area.⁵⁴

In 1792, Yale had a footprint in the city that was an unimpressive 100,000 square feet—which is a little more than two acres—and by a century later it had barely grown (Figure 4).⁵⁵ By 2000, however, that footprint had increased to 835 acres to include hundreds of buildings, athletic fields, nature preserves, and a medical center.⁵⁶ A pivotal moment in the development of New Haven's built environment was Yale's construction and opening of nine residential colleges—out of today's 14—between 1930 and 1935.⁵⁷ In 1931, as the construction of the colleges began, more than 11,000 of the city's 68,000 working people were idle and 18,000 city families had no full time wage earner.⁵⁸ In direct contrast, Yale was purchasing

⁵⁴ A. B. Hill. *City of New Haven, Connecticut*. [map]. Scale [1:2,400]. Boston, Massachusetts: Geo. H. Walker & Co., 1893. <https://curiosity.lib.harvard.edu/scanned-maps/catalog/44-990095632190203941>

⁵⁵ Arnold Guyot Dana. *New Haven's Problems: Whither the City? All Cities?*. (Tuttle, Morehouse & Taylor Company, 1937.)

⁵⁶ Yale University Office of Facilities. "A Framework for Campus Planning." *Yale University*, 2000.

⁵⁷ David McCullough III. "Town, Gown, and the Great Depression." *Yale Historical Review*, 2020. Available at: https://historicalreview.yale.edu/sites/default/files/files/YHR_YaleIssueMcCullough2.pdf

⁵⁸ McCullough III. "Town, Gown, and the Great Depression".

blocks of cheap city property and planning to replace old houses and businesses with massive, tax-exempt buildings. Their main goal was to reunite the slowly dividing university and bring students back into university dorms from off-campus housing, especially those in fraternities.⁵⁹ While beneficial to the university, it directly harmed the city through the gross expansion of tax-exempt property and by slashing the economic benefits that undergraduates had been contributing to businesses around the city. Moreover, this expansion was actively reducing the taxable property in New Haven, at a time of crisis when taxes were already high, the city was in massive debt, and they were facing extreme financial despair. This five year period would have a long term legacy on the continued expansion of Yale and the continued gentrification of the city.

The conversation surrounding Yale's expansion and tension with the city, including debates over its tax-exempt privilege, has continued to the present day. The legacy is also clear in the distribution of greenspace in the land cover, with most of the downtown vegetation concentrated in and around Yale's campus. Without Yale's extensive presence, perhaps New Haven would have less of a stress on housing availability, affordability, and space to develop. Not only does the university directly consume space, but it attracts a population of people that also consume valuable real estate that could otherwise be inhabited by the city's residents. The Homebuyer Program that Yale offers its faculty provides a \$7,500 payment for purchasing a house within the city, followed by annual payments of \$2,500 for up to 10 years.⁶⁰ While contributing revenue to the city, this program also encourages the predominantly white, high income Yale faculty to move into the city and take up housing and space, potentially contributing to gentrification and an increase in property values.

⁵⁹ McCullough III. "Town, Gown, and the Great Depression".

⁶⁰ "Homebuyer Program." *It's Your Yale*. 2020. Available at: <<https://your.yale.edu/work-yale/benefits/yale-signature-benefits/homebuyer-program>> [Accessed 12 December 2020].

Lasting Impact

Equitable housing and safe neighborhoods are key determinants of health, and Black people are often barred from these as a result of structural racism, including the legacies of racist housing policies.⁶¹ Redlining has resulted in lower property values and lower home ownership among Black neighborhoods and populations. Urban renewal policies and plans caused the destruction of Black communities, followed by perpetual social and economic disadvantage. Environmental injustice can take shape in subtle forms and silently contribute to negative health outcomes, such as increased presence of pavement contributing to the unequal development of urban heat islands and thus heat stress. There is an inextricably connected relationship between the long history of systemic racism in the United States and the varied environmental experiences across demographic groups. Recognizing, understanding, and evaluating the extent of this relationship is a crucial aspect of combating inequity in health and environmental outcomes.

⁶¹ M. T. Bassett and S. Galea. "Reparations as a Public Health Priority—A Strategy for Ending Black–White Health Disparities." *New England Journal of Medicine*, 383(22), (2020): 2101-2103.

Methods

This analysis of heat stress vulnerability throughout New Haven is composed of two parts: exposure and sensitivity. The goal of the exposure analysis is to identify variation in temperature across the city in order to pinpoint areas of higher heat exposure. Tree cover, impervious surfaces, and proximity to water are included as environmental factors within the exposure analysis in order to help understand possible influences on temperature. The goal of the sensitivity analysis is to use social factors as indicators of populations that are less equipped to respond and be resilient when faced with heat stress. The components of this section include data on age, income, race, and ethnicity, which each capture sensitivity to the health risks, resilience, or disproportionality of heat exposure.

Exposure: Temperature

Seasonal Variability in Temperature: Autumn

The temperature measurements in this study were collected in the autumnal months of October and November. This contrasts with the usual trend of studying heat stress and the urban heat island effect at its peak, in the summer. It is important to note, however, that while variation in urban temperatures is less extreme in autumn, the areas with the greatest difference from the average temperature are consistent with those in the summer.⁶² The physical factors influencing the UHI effect magnify heat, so during lower temperatures in autumn, those factors have a less significant impact. Thus, by measuring and analysing temperatures in autumn, one can highlight the differences within the city that are closer to those seen year-round and aligning with annual averages.⁶³ Additionally, measurements in autumn help to point out the hot spots,

⁶² Yao Yuan et al. "Seasonal variations of the urban thermal environment effect in a tropical coastal city." *Advances in Meteorology* (2017).

⁶³ Yan Chen, Ning Zhang, and Yan Zhu. "High-Resolution Simulations of the Urban Thermal Climate in Suzhou City, China." *Atmosphere* 10, no. 3 (2019): 118.

rather than cool spots.⁶⁴ Specifically in regards to the urban heat island, autumn has a more stable UHI intensity over a decade which is good for understanding the baseline intra-urban differences in temperature.⁶⁵ Summer temperatures vary much more and at more extreme temperatures, so in knowing the autumn variation one can better predict the spatial variance in temperature throughout the city in a year with a particularly hot summer.⁶⁶ Understanding this baseline could help identify neighborhoods that are at risk of higher heat exposure than the average expected temperature for the city.

Data Collection via Biking

To answer my research questions, I need data on the temperature distribution throughout New Haven, at the surface level. To collect this information, I used a NewSky Smart T sensor and attached it to the handlebars of a bike. This sensor collects data on the time, latitude, longitude, temperature, and humidity as you move on the bike. I chose to collect data from the sensor at 1 second intervals in order to have a large amount of temperature readings at many different points through the city. As the sensor collects the data, it communicates with the NewSky app, which then allows the data to be downloaded at the end of each bike ride.

Before embarking on any rides to collect data, I first designed five different transects throughout the city. My goal was to ride through every major neighborhood of the immediate New Haven Metropolitan Area, focusing primarily on residential areas in the densest part of the city. I referenced Home Owners' Loan Corporation Maps when designing the routes to ensure that I measure neighborhoods that were graded differently in 1937.⁶⁷ I wanted to make sure that

⁶⁴ Chen, Zhang, and Zhu. "High-Resolution Simulations of the Urban Thermal Climate in Suzhou City, China."

⁶⁵ Qingyan Meng et al. "Characterizing spatial and temporal trends of surface urban heat island effect in an urban main built-up area: A 12-year case study in Beijing, China." *Remote Sensing of Environment* 204 (2018): 826-837.

⁶⁶ Meng et al. "Characterizing spatial and temporal trends of surface urban heat island effect in an urban main built-up area."

⁶⁷ Nelson et al. "Mapping inequality: Redlining in New Deal America."

I could compare a redlined—or grade ‘D’—neighborhood with a highly graded neighborhood. I found that in New Haven this could be best done by comparing East Rock (Grade A) to The Hill (Grade D), however, I still included a few other routes in order to get a strong survey of the city.⁶⁸ I also consulted bike route maps through New Haven, from a safety standpoint, to ensure that riding along the transects would be feasible. Moreover, in terms of feasibility, I intended for each bike ride to be around 30 minutes long to avoid any major changes in the weather and to make sure each bike ride required similar levels of exertion to ensure there’d be consistency in speed.

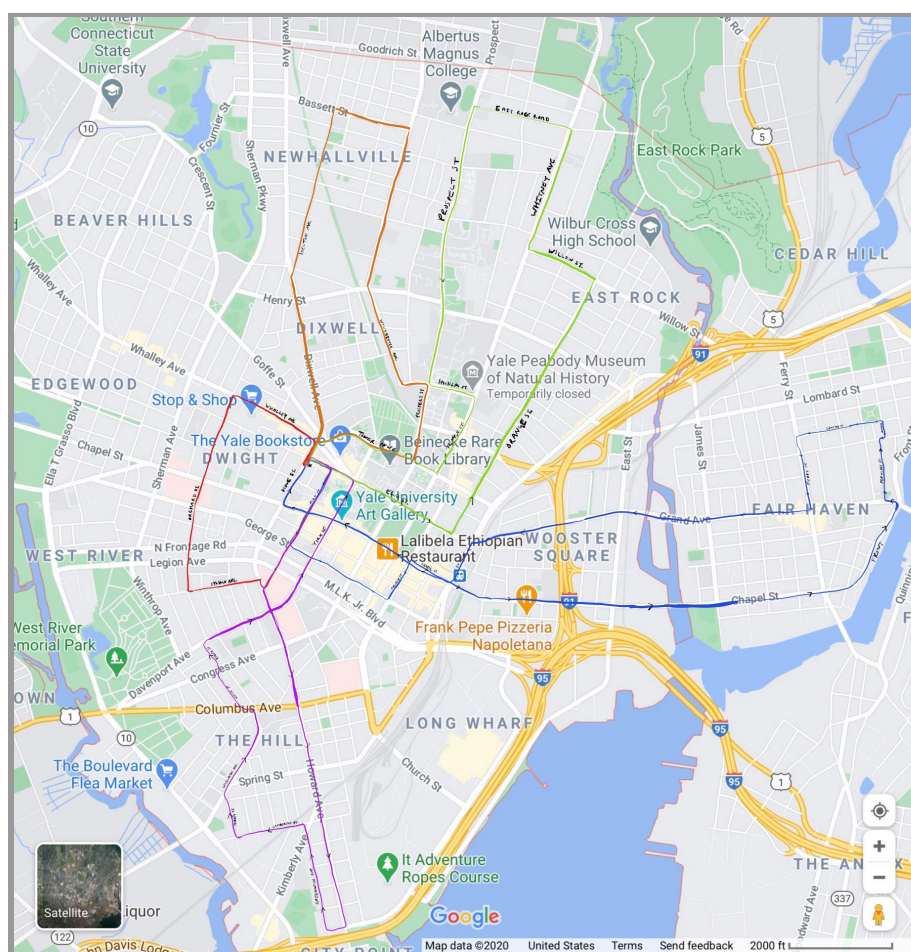


Figure 5. A map of the five transects used as bike routes to collect temperature data.

The resulting map of transects includes one for The Hill, Fair Haven, East Rock, and Dwight neighborhoods and a fifth that covers both Dixwell and Newhallville, but for this paper’s

⁶⁸ Nelson et al. "Mapping inequality: Redlining in New Deal America."

purposes will be called Dixwell (Figure 5). These five routes cover parts of the city that vary in land cover and some have nearby water bodies that could be influencing the local temperatures. When collecting data, each of the transects was repeated three times, over the course of different days. To minimize extraneous variables, all rides were completed between 11:30 AM and 3:30 PM which roughly encompasses peak sunlight and temperatures in the city.

Temperature Anomalies

The temperature values of each ride were converted to anomalies from the mean city temperature at the time of data collection. The mean background temperature values are based on measurements at the local weather station, Tweed Airport, which is located just outside of the city. Weather data collected here is used to inform weather applications and websites, and therefore, the general public. Developing the anomalies from this data has the added bonus of showing the difference between the communicated temperatures and those actually observed within a neighborhood. These anomalies reflect the difference between the temperatures in a neighborhood from the city and help to highlight areas warmer and cooler than average. Since there is variance in the days, times, and weather conditions when the data was collected, the anomalies neutralize those temporal factors and make it possible to compare heat differences between the five neighborhoods.

Geography

New Haven has a population of about 130,250 people within a land area of about 18.7 square miles.⁶⁹ Heat exposure and sensitivity in the city were examined at two geographic scales: neighborhood (n=5) and U.S. Census tract (n=19). Census tracts are subdivisions of counties designated by the U.S. Census and each one contains between 1,200 and 8,000

⁶⁹ "QuickFacts: New Haven City, Connecticut."
<https://www.census.gov/quickfacts/newhavencityconnecticut>

people.⁷⁰ There were 19 tracts within the five transects of my bike routes and each tract was assigned to the neighborhood it helped represent. Census tract designations tend to have geographic attributes that compliment neighborhood boundaries, which was essential for my neighborhood-level analysis. Census tracts were used as the geographic boundary for analyzing temperature data with other variables, such as income or age. This was done by calculating the mean anomaly for each tract and ensured scalar consistency across variables. This small geographic scale was made possible by the availability of data at the tract level for all of the social factors (age, income, race, ethnicity). The most recent data provided by the Census at the tract level for New Haven is from the 2019 American Community Survey 5-Year Estimates; this served as the source of all social factor data.

Exposure: Land Cover

Quantitative data on tree cover, defined as the area of ground covered by a layer of leaves, branches, or stems when viewed from above, was sourced from a study on tree canopy metrics by neighborhood in New Haven.⁷¹ A Spearman's correlation was run to determine the relationship between 19 tree and temperature values. There was no statistically significant correlation between tree and temperature ($r_s = -0.28$, $n = 19$, $p > .05$). Maps from the National Land Cover Database 2016 Land Cover Science Product provided geographic data on tree cover and impervious surfaces in the city.⁷² This geographic data allowed for visual analysis and the discussion of possible relationships between temperature and land cover.

⁷⁰ "Glossary." *The United States Census Bureau*, September 16, 2019.

https://www.census.gov/programs-surveys/geography/about/glossary.html#par_textimage_13.

⁷¹ Stacey Maples, "Urban Tree Canopy Neighborhood Metrics for New Haven, CT," *DataHaven* (New Haven, CT: Urban Resources Initiative, December 31, 2010),

<https://www.ctdatahaven.org/data-resources/urban-tree-canopy-neighborhood-metrics-new-haven-ct>.

⁷² J. Dewitz. "2016 Science Products: U.S. Geological Survey data release." *National Land Cover Database (NLCD)*, 2016. <https://doi.org/10.5066/P96HHBIE>.

Exposure: Water Proximity

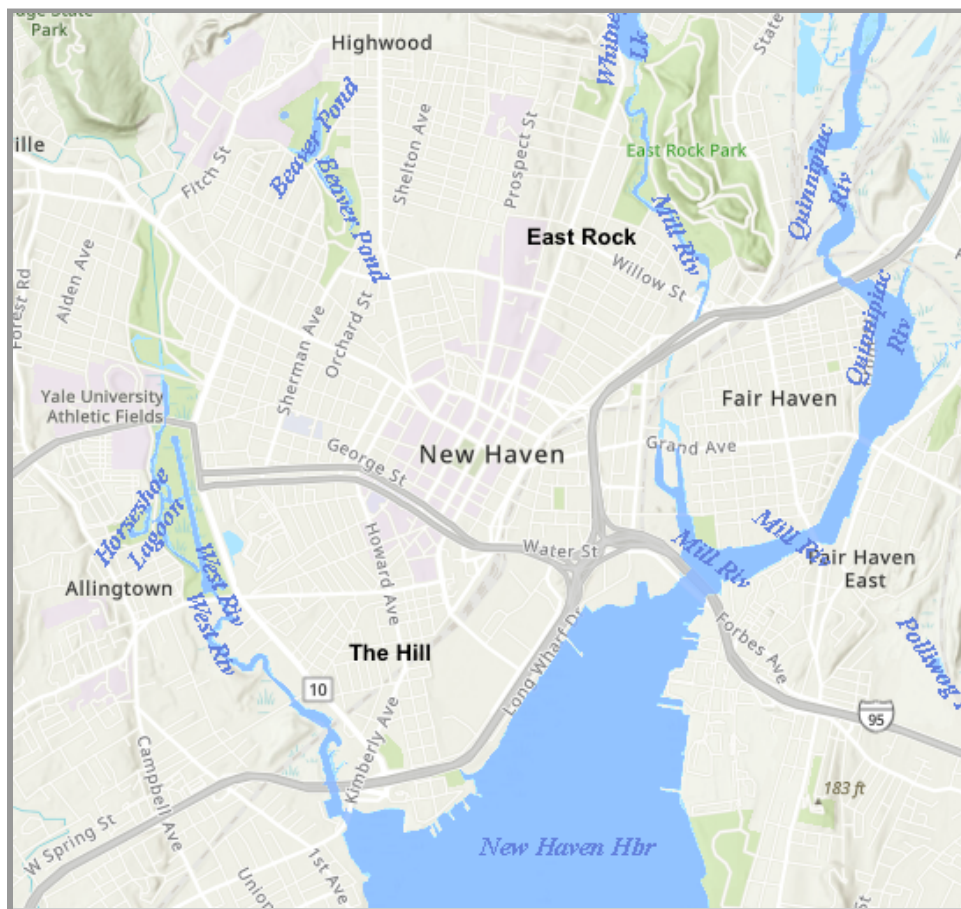


Figure 6. A labeled map of the bodies of water surrounding The Hill, East Rock, and Fair Haven neighborhoods.

Data Collection

Three neighborhoods, out of the five being analyzed, are proximal to water (Figure 6). This means they have land area that is immediately bordered by a river or other large body of water. Fair Haven is bordered on two sides by the Quinnipiac River and on another by Mill River. The Hill is bordered on two sides by water, one being the New Haven Harbour and the other West River. East Rock is bordered on one side by Mill River. To analyze the influence of proximity to water on temperature, quantitative data on areal hydrography was sourced from the 2020 U.S.

Census Bureau Physical Features data.⁷³ The area hydrography data includes ponds, lakes, oceans, swamps, glaciers, and the area covered by large rivers, streams, and/or canals.⁷⁴ However, these specific neighborhoods primarily contain only rivers and harbors, and any neighborhood that had an area of water smaller than a river was not included in this analysis. For example, one of the census tracts in the Dixwell neighborhood is proximal to Beaver Pond, but given the small area of the water and the forest area that separates it from the neighborhood streets, it was not considered influential. The data is provided in square meters (m²) by census tract.

Data Analysis

Once the total area of water per census tract was determined from the Physical Features data, I analyzed the intra- and inter-neighborhood differences between the water proximity and temperature relationship. To establish the influence of water proximity within a neighborhood, I calculated the mean temperature anomaly for all tracts with water (n=7), which are only in East Rock, Fair Haven, and The Hill. I then compared this with the mean anomaly for tracts without water in those same three neighborhoods (n=8). These tracts were all grouped by neighborhood (East Rock, Fair Haven, The Hill) which allowed for a temperature comparison between areas within a neighborhood. For example, given the mean anomalies for water proximal and non-proximal areas in Fair Haven, I could evaluate which group was warmer or cooler to see if water had a cooling effect, as expected. I conducted a similar analysis to evaluate the inter-neighborhood relationship. The average temperature anomaly for all census tracts with water (n=7) and without water (n=12) was calculated to see the impact of water on temperature across the whole city.

⁷³ "TIGERweb/TigerWMS_PhysicalFeatures (MapServer)." Census.gov, 2020.
https://tigerweb.geo.census.gov/arcgis/rest/services/TIGERweb/tigerWMS_PhysicalFeatures/MapServer.

⁷⁴ Hornsby, Cory. "TIGERweb Geography Descriptions." Census.gov, 2020.
https://tigerweb.geo.census.gov/tigerwebmain/TIGERweb_geography_details.html#AREALHYDRO.

Sensitivity

Data used for this analysis was sourced from the U.S. Census Bureau 2019 American Community Survey (ACS) 5 year estimates at the census tract level. For each social factor I calculated the percentage of sensitive individuals out of the total population, in each census tract (Table 1). Once all data was collected and summarized by census tract, a Spearman analysis of each social factor with temperature was run to examine the statistical relationships.

Data Descriptions for Social Factors

All data is from the 2019 American Community Survey: 5-year Estimates for New Haven, CT.

Factor	Values	Description
Age	Percent of population age 65+	Total amount of population in an at-risk age group
Income	Percent of population in poverty	Total amount of population with poverty status designation
Race	Percent of people of color	Total amount of people with a race other than white
Ethnicity	Percent of Latinx residents	Total amount of people that are Latino

Table 1. A description of the values used to represent each social factor in the sensitivity analysis.

Age sensitivity was determined to be the percentage of individuals age 65 or older, as consistent with other studies on heat related illness demographics.⁷⁵ Although infants are among the age groups considered vulnerable to heat, they were not included because the smallest census age grouping is 5 years and younger which does not allow for the needed specificity.

⁷⁵ Bailes and Reeve. "Prevention of Heat-Related Illness."

Income sensitivity is represented by the percentage of individuals living in poverty status, a designation used in the 2019 ACS 5 year estimates. Poverty status is determined by whether a household has an income above or below its poverty threshold (a dollar amount).⁷⁶ There are 48 possible poverty thresholds and each person or family is assigned one based on the size and age of the family. The nuance of this designation helps capture the sensitivity, provides a tract level analysis, and the data is calculable by percent of total population per census tract. While income sensitivity may also be represented by median household income as compared with area income, the poverty status figure helps to pinpoint the most vulnerable populations.

Race sensitivity is the percentage of non-white individuals, which represents the most inclusive grouping for people of color. Since the Census collects data for a wide variety of racial identities—including those identifying with multiple—using total non-white helps capture all people of color. This factor is meant to estimate the people facing obstacles caused by deeply rooted systemic and institutional racism which has a meaningful influence on an individual's health risks and outcomes, housing patterns, and socio-economic obstacles. As it pertains to heat stress specifically, predominantly-minority neighborhoods that were redlined tend to be warmer and communities of color tend to suffer disproportionately from heat related illness.⁷⁷⁻⁷⁸ Using the percent non-white data provides a figure that helps measure this sensitivity at the tract level.

Ethnicity sensitivity measures the percentage of people that are Latinx, which is grouped separately from race because it represents a different component of identity. Latinx individuals are people of color, yet often are grouped within white racial categories, so using this data helps ensure that all people of color are included in the analysis.

⁷⁶ US Census Bureau. "How the Census Bureau Measures Poverty." The United States Census Bureau, August 26, 2020.

<https://www.census.gov/topics/income-poverty/poverty/guidance/poverty-measures.html>.

⁷⁷ Hansen et al. "Vulnerability to extreme heat and climate change: is ethnicity a factor?."

⁷⁸ Hoffman et al. "The effects of historical housing policies on resident exposure to intra-urban heat: A study of 108 US urban areas."

Results

The purpose of this analysis is to determine the nature of heat exposure and sensitivity for The Hill, Fair Haven, East Rock, Dixwell, and Dwight neighborhoods in New Haven. The results for the temperature, land cover, and water proximity analyses are provided first to establish the areas with higher heat exposure and examine some variables that may be contributing. Then, the sensitivity analysis results are shown for age, income, race and ethnicity to indicate the areas in the city that are most sensitive to high temperatures. Finally, data from the two sections are analyzed and compared together to develop an understanding of overall vulnerability to heat. The results from this analysis are shown in Table 2-7 and Figures 7-15.

Exposure: Temperature

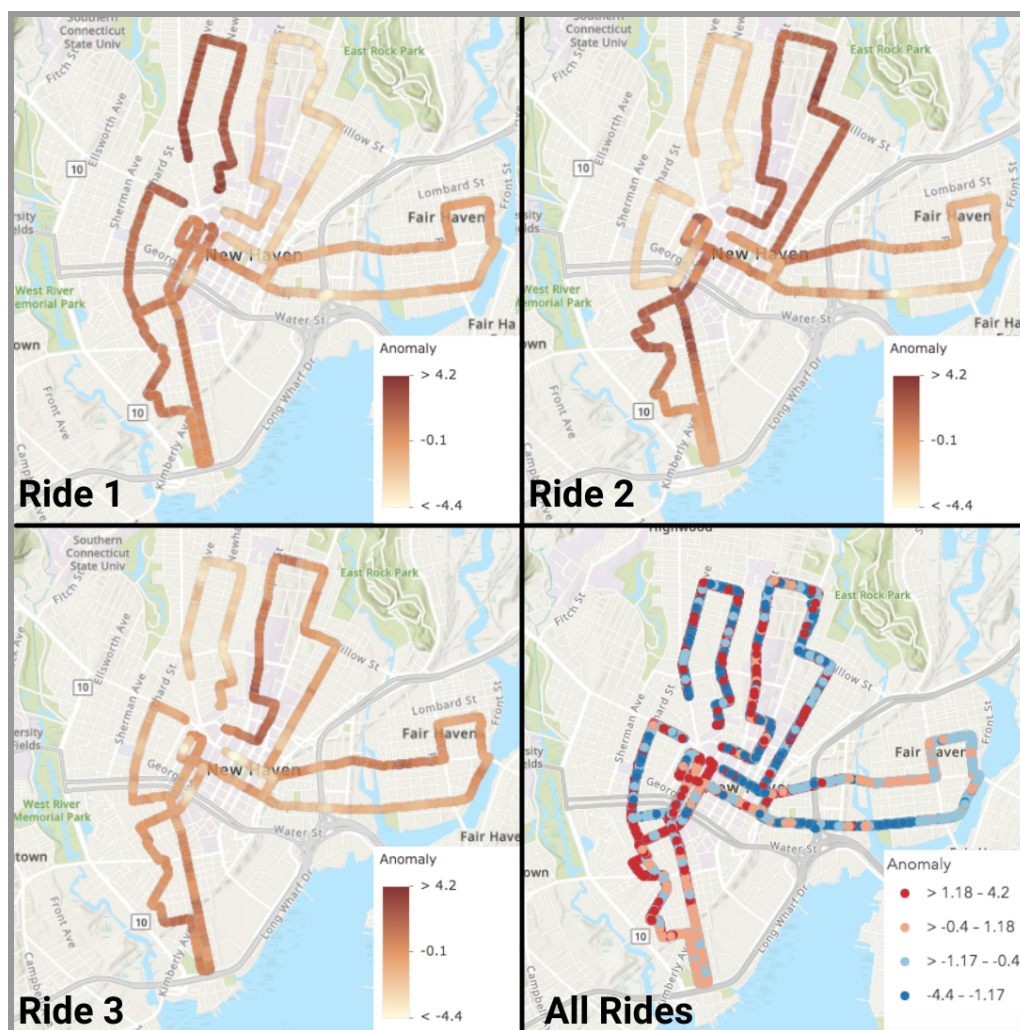


Figure 7. A grid of maps that display the temperature anomaly variation across transects for each set of rides and for all of them combined.

The data collected from the NewSky sensor when biking along the chosen transects revealed clear variation in temperature across the city. Since the temperature data was collected on various days in October and November, with different background weather conditions, some variation was expected. As shown in Figure 7, some neighborhoods varied greatly throughout the three different rides, especially Dixwell, Dwight, and East Rock. Given the known influence of environmental factors, these large shifts from majority cool to majority warm are most likely a

result of the interaction between the weather conditions and the built environment. However, when all of the temperature anomalies are combined into one visualization, the consistency of The Hill and Fair Haven stands out (Figure 7). The Hill was consistently warm with only a few cool anomalies recorded, while Fair Haven was consistently cool with only a few warm anomalies recorded. Each ride for each neighborhood had between 1000 and 2000 data points, so while it's helpful to understand how these anomalies varied across rides, the summary statistics can help us draw more conclusions. For the remaining results, data from all rides are used to develop the analysis.

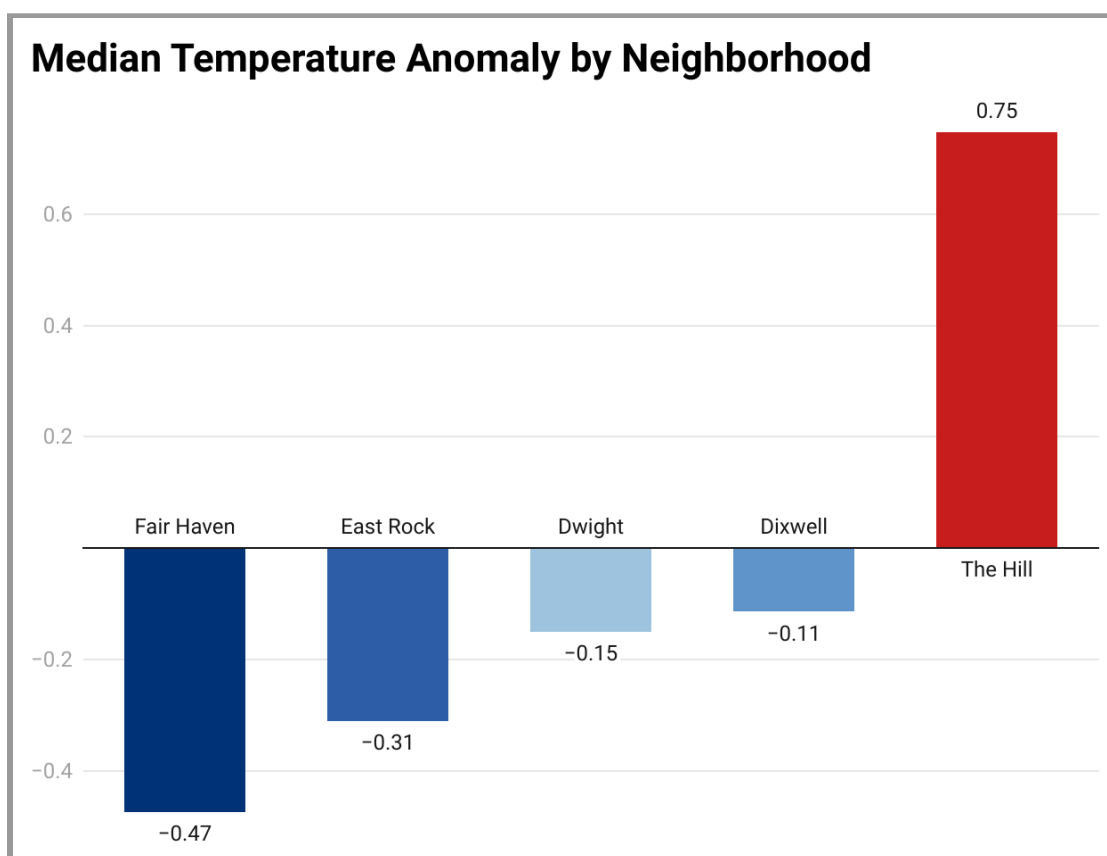


Figure 8. A bar chart showing the median temperature anomaly by neighborhood.

Using the median anomaly for each neighborhood to evaluate temperature exposure allows for a strong comparison since the median is a resistant statistic. As seen in Figure 8, the median across neighborhoods tended to run cool, as indicated by negative anomaly values. The

Hill had the highest median temperature anomaly—and the only positive one—at 0.75°F (Figure 8). Fair Haven was the coolest neighborhood, with an average median of -0.47°F across rides. The cool temperature anomalies in a majority of neighborhoods reflects the expectation that autumnal urban heat island analysis closely resembles annual averages. However, autumnal urban heat islands tend to also reveal hot spots effectively. Here, it is shown that The Hill is the warmest neighborhood in the city.

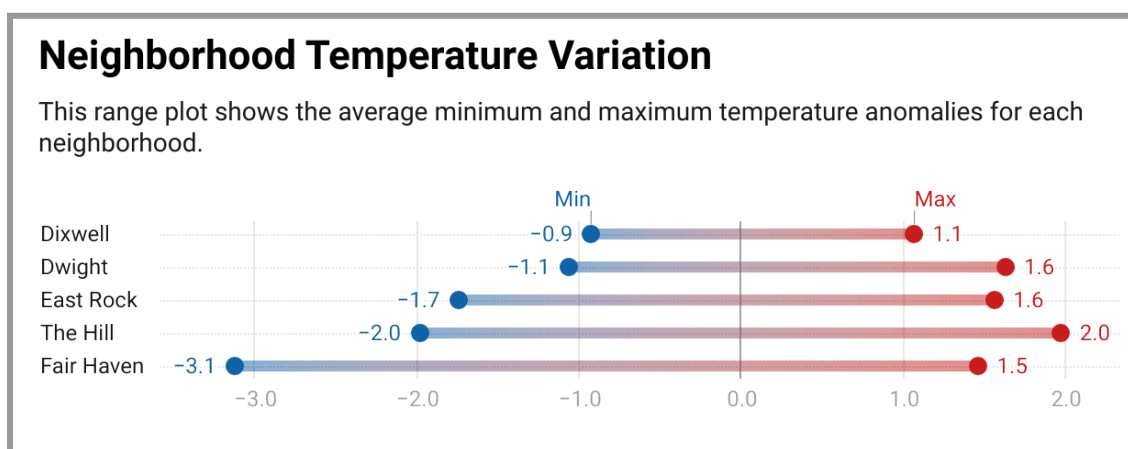


Figure 9. A range plot showing the variation in temperature anomalies for each neighborhood.

Given the variation that was observed across rides in Figure 7, an analysis of the average minimum and maximum temperature anomalies was conducted. This provides a quantitative depiction of the same phenomenon and measures the consistency of temperatures in a neighborhood. Figure 9 shows that Dixwell has the smallest average temperature range, the warmest average minimum, and the coldest average maximum temperature. The lack of variation, relative to other neighborhoods, suggests that Dixwell is unlikely to have seasonal extremes and that it may have a more homogenous built environment. However, since this autumnal data and Dixwell has the second highest median, it is important to note that in summer months the relationship to the city average may change and rise above average. In contrast, Fair Haven has the largest range of temperature anomalies (difference of 4.6°F) and the coldest minimum temperature indicating large variation in heat distribution. Since Fair Haven

also had the lowest median anomaly, it is possible that there are some warmer spots within the neighborhood, but it is consistently cool. These ranges are important for understanding how overall increases in temperature will impact the neighborhoods individually. An extreme heat even can exacerbate any variations in a neighborhood, especially impacting hot spots.

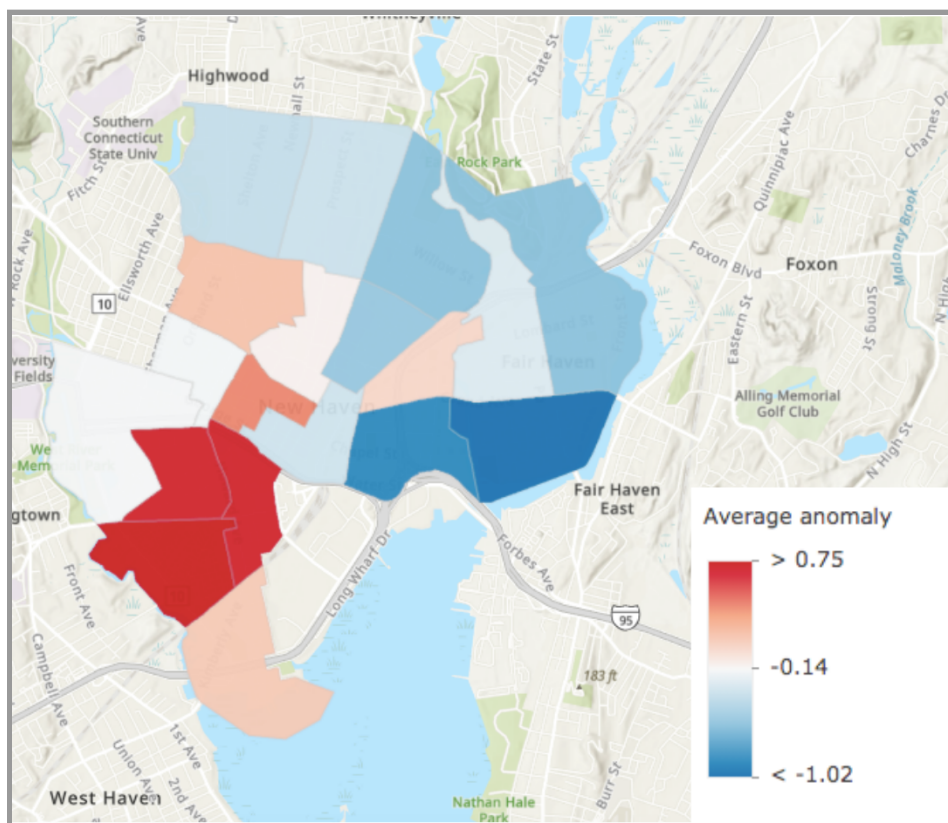


Figure 10. A map showing the average temperature by census tract.

Since census tracts are the geographical base for this data analysis and used to analyze temperature with other social factors, a calculation of average anomaly by census tract was conducted. The results indicate that the warmest census tracts are in The Hill and the coolest are in Fair Haven (Figure 10). Most census tracts in Dixwell and Dwight have average anomalies that are non-extreme, with a combination of both slightly warm and slightly cool areas. Similarly to the visualization of rides in Figure 7 and the range plot in Figure 9, this analysis helps point to variation within neighborhoods, but at a more nuanced scale. Here, it is clear that although Fair Haven is the coolest neighborhood, there's still one tract that has a positive average anomaly.

East Rock has similar results, with the area being largely cool but having one census tract closer to downtown that is slightly warm.

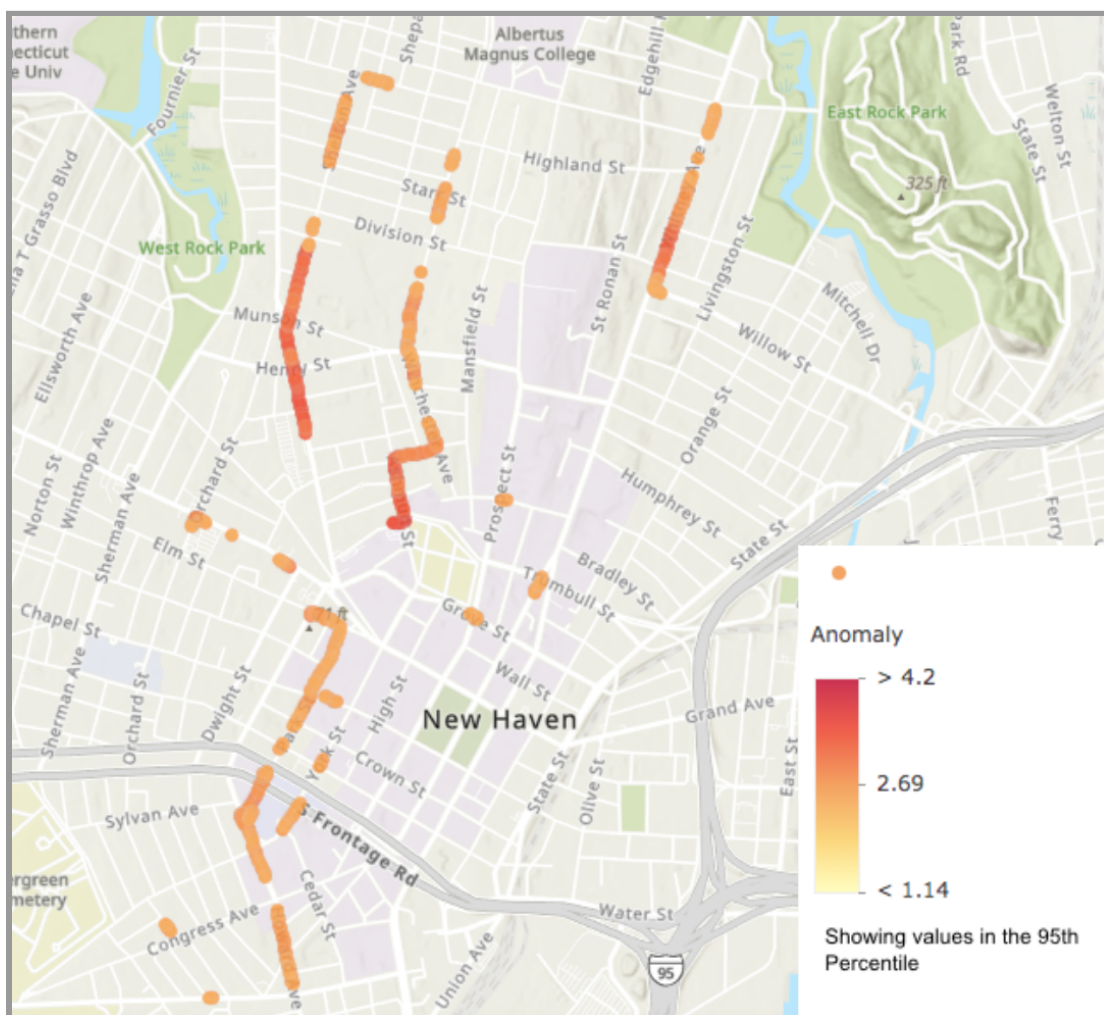


Figure 11. A map showing the location of temperature values in the 95th percentile of all collected data.

To get an even closer look at the nature of heat exposure and variation in the city, the full data set of anomalies were filtered geographically by various quantiles. The warmest 25% of data ranged from 1.15°F to 4.23°F. The 90th percentile of values was 2.07°F and the 95th percentile was 2.43°F. Figure 11 shows the geographic distribution of all values at or above the 95th percentile, revealing the hot spots across the city. The map is a much more limited view of the city than some other figures, which was done to allow for more clarity and enabled by the

absence of any hot spots in Fair Haven. These results are important because they indicate that Dixwell had the most recorded and most extreme hot spots, despite not having the highest median. The hot spot analysis also shows East Rock as an area with some extreme hot spots, which is notable since this was the second coolest neighborhood. Consistent with other temperature results, The Hill had lots of hot spots as well. These hot spots provide important areas of attention since summer temperature will exacerbate some of the autumnal extremes here, which are already as high as 4.2°F higher than the city average.

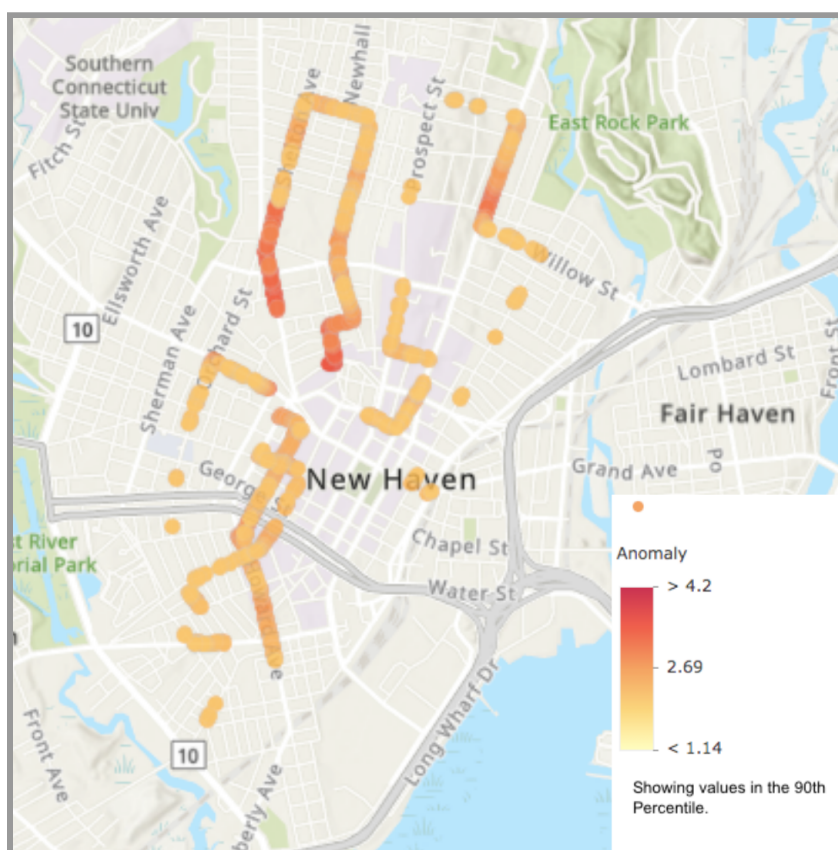


Figure 12. A map showing the location of temperature values in the 90th percentile.

The data at the 90th percentile and above—while less nuanced than the 95th—provides seasonal insight. Since the 90th percentile is 2.07°F warmer than the city average, as measured in autumn, many of these values could be more extreme in the summer or during an extreme

heat event. While still concentrated in similar areas as the 95th percentile map, this one helps show more areas warranting attention. Most notably, it indicates, more than the 95th percentile, that Dwight could be an area of interest for hot spots. These areas of high heat exposure are important for developing urban heat mitigation plans.

Temperature Summary by Neighborhood			
Neighborhood	Minimum anomaly	Maximum anomaly	Median anomaly
The Hill	-3.0	3.2	0.75
Dixwell	-2.6	4.2	-0.11
Dwight	-2.6	3.3	-0.15
East Rock	-3.7	3.4	-0.31
Fair Haven	-4.3	2.4	-0.47

Table 2. The minimum, maximum, and median temperature anomalies by neighborhood. Rows are sorted high to low according to values in the Median anomaly column and colors (dark to light) indicate high to low values as well. The length of bars in the Minimum and Maximum anomaly columns correspond to the extremity of the value from zero.

Contrasting the range plot in Figure 9, Table 2 provides a summary of important values for each neighborhood, including a raw range of anomalous values. Instead of showing the average minimum and maximum values, this table provides the recorded extremities and the median. The data in this table reflects what is seen in the hot spot maps (Figures 11 and 12). Dixwell has the highest maximum, followed by East Rock and Dwight. Fair Haven still remains the coldest neighborhood with the lowest minimum, maximum, and median anomaly values. The Hill is the warmest with a much higher median anomaly than any other neighborhood and among those with maximums at or above the 99th percentile (3.2°F).

Exposure: Land Cover

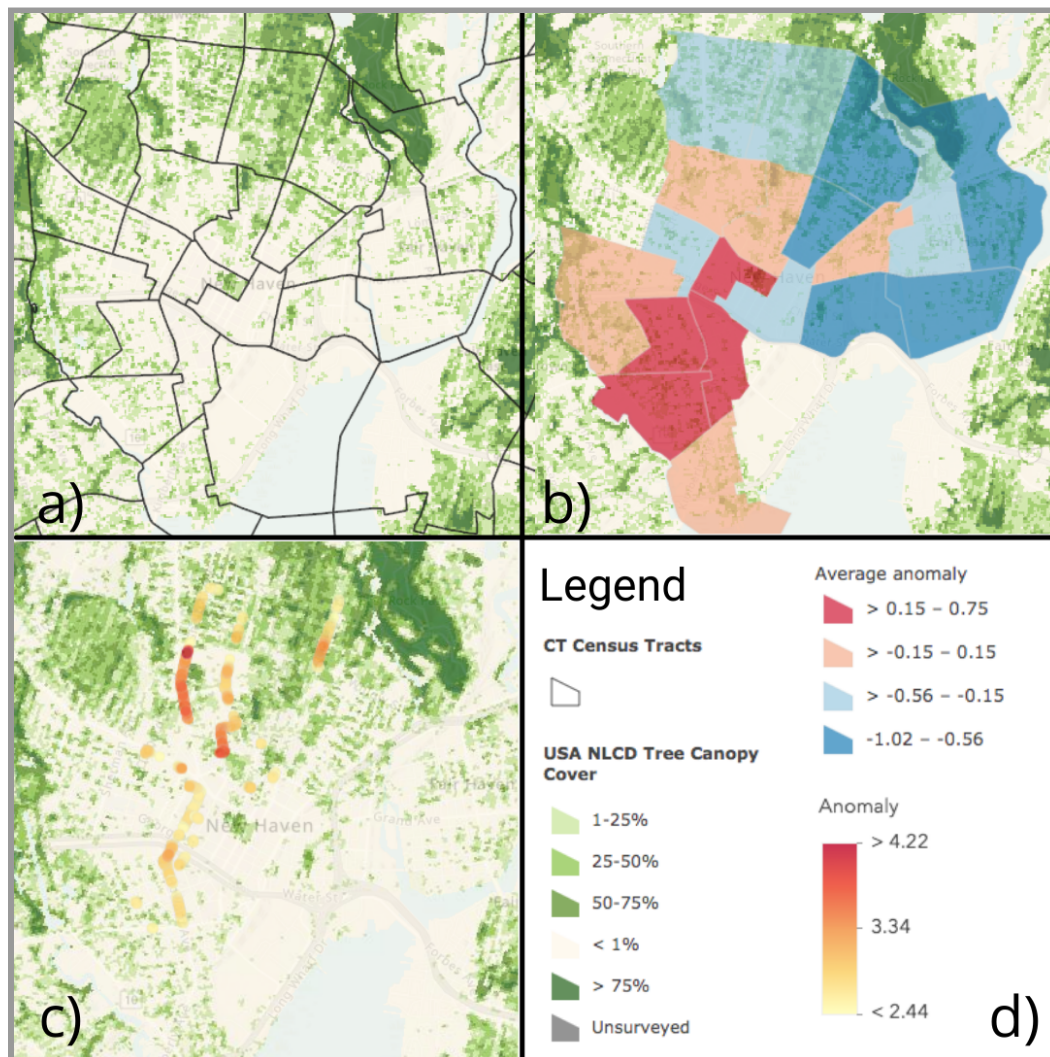


Figure 13. Visual tree cover analysis. a) Showing the tree cover overlaid with census tract borders. b) Showing the mean temperature anomaly by census tract overlaid on tree cover. The color scale is classified by quartiles. c) Showing the temperature anomalies in the 95th percentile overlaid on tree cover. d) The legend for colors and values in each grid.

The two neighborhoods with the most dense tree cover are Dixwell and East Rock, as seen in Figure 13. For East Rock, this aligns as expected with temperature since it has the second lowest median anomaly and some extremely cool values (Table 2). However, Dixwell has the second warmest median anomaly and lots of observed hot spots. Perhaps, the areas where data was collected lacked as much tree cover as what is seen in the larger Dixwell area,

resulting in warmer temperatures. By comparing Figure 13a with Figure 13c, areas lacking tree cover and with more hot spots indicate possible next steps for heat mitigation in this neighborhood. Also notable is that Figure 13b shows lots of cool census tracts in Fair Haven with very little tree cover. This discrepancy hints that the coastal positioning of Fair Haven is having an influence on its cool temperature. The proximity to a large body of water allows for evaporative cooling which reduces the role of tree cover in providing cooler temperatures. Dwight, Dixwell, and most of The Hill, are not proximal to bodies of water so tree cover plays a larger role in their heat exposure. The areas in Dwight in the Hill that are closest to the center of the city have the least amount of tree cover, and the most hot spots. Given the higher amounts of tree cover in East Rock and Dixwell and those neighborhoods also having some of the most extreme hot spots (Figure 11), existing mitigation efforts should be expanded to these hot spots or other strategies should be explored.

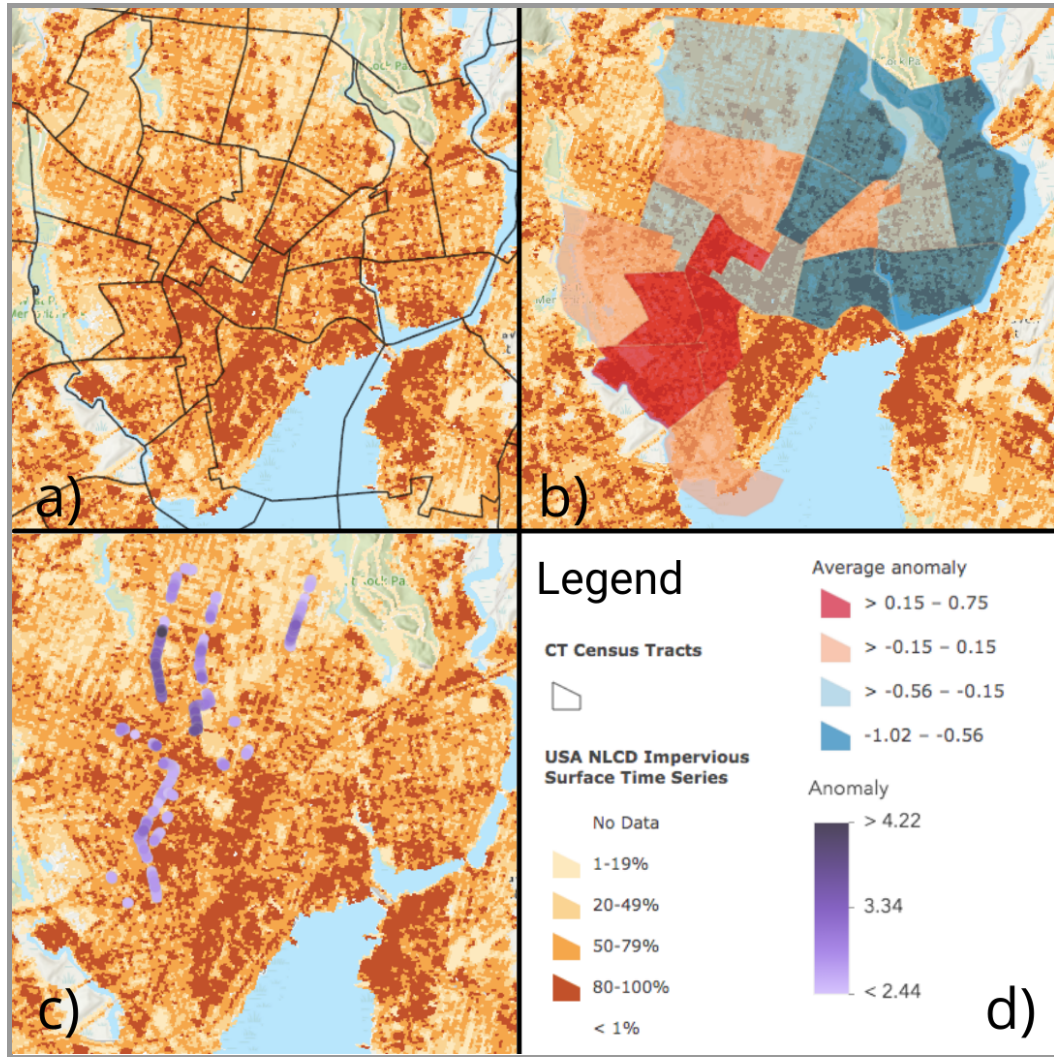


Figure 14. Visual impervious surface cover analysis. a) Showing the impervious surface cover overlaid with census tract borders. b) Showing the mean temperature anomaly by census tract with impervious surface cover. c) Showing the temperature anomalies in the 95th percentile with impervious surface cover. d) The legend for colors and values in each grid.

Looking at Figure 14a, it is clear that census tracts in the center of the map have the most dense quantity of impervious surface cover. This means these areas have more paved roads, parking lots, and other surfaces that absorb heat and radiate heat. Most of these tracts are part of The Hill or Fair Haven. As the warmest neighborhood, this is expected for The Hill. Despite the quantity of impervious surfaces, Fair Haven is the coolest neighborhood. There is also a dense concentration in the one Fair Haven census tract that has only one water-bordered

side. However, this tract happens to be very cool— in the bottom 25% of all temperature anomalies (Figure 14b). Impervious surface coverage is lowest in parts of East Rock, which matches the expected low temperature values in those tracts (Figure 14b). It seems that the hot spots shown in Figure 14c have lots of overlap with areas of dense impervious surface coverage in The Hill, indicating a possible path for mitigation. The hot spots in Dixwell and East Rock do not align well with dense impervious surface coverage, so perhaps this issue could be better addressed by increasing tree cover.

Exposure: Water Proximity

Intra-neighborhood Analysis				
TRACTS WITH WATER			TRACTS WITH NO WATER	
Neighborhood	Area of Water (m ²)	Average Anomaly	Neighborhood	Average Anomaly
The Hill	528871	0.43	The Hill	0.70
East Rock	34505	-0.59	East Rock	-0.32
Fair Haven	605609	-0.69	Fair Haven	-0.13

Inter-neighborhood Analysis	
OVERALL	
Average Anomaly for Areas with Water	-0.35
Average Anomaly for Areas with None	0.06

Table 3. Water and Temperature Analysis. The Intra-neighborhood Analysis table shows the average temperature anomaly for areas with and without water in water proximal neighborhoods. The Inter-neighborhood Analysis table shows the average anomaly for areas with and without water across the whole city.

Focusing just on the neighborhoods that are near water first, the data indicates that temperature is influenced by water. Three neighborhoods are near water: The Hill, East Rock, and Fair Haven. Each of the neighborhoods have some census tracts with water and some without water. The census tracts with water all had cooler average anomalies than the census tracts without water within neighborhoods. The Hill and East Rock census tracts with water were 0.27°F cooler than those without (Table 3). Fair Haven census tracts with water were 0.56°F cooler than those without, the larger difference most likely attributable to the larger amount of water area in Fair Haven (Table 3).

When comparing all census tracts with water to all census tracts without water, meaning Dwight and Dixwell are now included, a similar trend was observed. Census tracts across the

whole city with water had an average anomaly of -0.37°F compared to those without water having an average anomaly of 0.06°F . This amounts to a difference of 0.43°F , nearly half a degree.

Sensitivity

Age Sensitivity by Neighborhood			
Neighborhood	Total People	Amount At-risk	Percent (%) ▼
Dixwell	12,453	1,277	10.3
Dwight	7,672	745	9.7
East Rock	15,572	1,512	9.7
The Hill	18,408	578	3.1
Fair Haven	23,883	694	2.9

Table 4. A table of the total people, amount over 65 yrs, and percent over 65 yrs by neighborhood. Rows are sorted high to low according to values in the Percent (%) column and colors (dark to light) indicate high to low values as well.

Table 4 shows that Dixwell has the highest percentage of individuals aged 65 or older at 10.3%, with Dwight and East Rock closely following at 9.7%. The Hill and Fair Haven have much lower portions of elderly individuals in their areas, despite being the most populous neighborhoods. This indicates that Dixwell has the highest sensitivity to heat stress based on age. None of the neighborhoods had disproportionately high age sensitivity. The city of New Haven has about 16.3% people aged 65 or older overall and these census tracts within my analysis are only representing about 6% of that total.⁷⁹ This suggests that areas within New Haven county, but not included in my analysis, have larger populations of elderly individuals.

⁷⁹ "QuickFacts: New Haven City, Connecticut." (2019). *Census Bureau QuickFacts*
<https://www.census.gov/quickfacts/newhavencityconnecticut>

Income Sensitivity by Neighborhood

Neighborhood	Total People	Amount in poverty	Percent (%) ▼
Dixwell	12,453	4,715	37.9
The Hill	18,408	6,465	35.1
Dwight	7,672	2,348	30.6
Fair Haven	23,883	7,220	30.2
East Rock	15,572	2,329	15.0

Table 5. A table of the total people, amount in poverty, and percent in poverty by neighborhood. Rows are sorted high to low according to values in the Percent (%) column and colors (dark to light) indicate high to low values as well.

Table 5 displays the income sensitivity by neighborhood, with the percentage of individuals in poverty serving as the primary metric. Dixwell has the highest level of income sensitivity with 37.9% of its population living in poverty. Not too far behind is The Hill at 35.1%, Dwight at 30.6%, and Fair Haven at 30.2% impoverished. At less than half of the highest poverty percentage, East Rock has the lowest amount of individuals in poverty at 15%. This data makes clear that Dixwell is a high level of income sensitivity, with The Hill not far off, and these neighborhoods should be prioritized in efforts to improve heat adaptation.

It's important to note that The Hill, Dixwell, and Fair Haven were redlined neighborhoods, graded 'D', and East Rock was graded 'A'.⁸⁰ This stark contrast in income within these communities—many decades later—signals the lasting impact of discriminatory practices like those carried out by the Home Owners' Loan Corporation. Since energy burdens are higher for low-income families, this social factor provides insight into the areas that are suffering from

⁸⁰ Nelson et al. "Mapping inequality: Redlining in New Deal America."

energy vulnerability, as well.⁸¹ This data can help inform efforts to help make these sensitive communities more resilient.

Race and Ethnicity Sensitivity by Neighborhood					
Neighborhood	Total People	People of Color	Percent (%) ▼	Amount Latinx	Percent (%)
Dixwell	12,453	10,771	86.5	1,693	13.6
Dwight	7,672	5,771	75.2	1,988	25.9
The Hill	18,408	10,838	58.9	7,117	38.7
Fair Haven	23,883	11,506	48.2	12,647	53.0
East Rock	15,572	5,512	35.4	1,805	11.6

Table 6. A table of the total people, amount identifying as people of color, and percent people of color by neighborhood. The last two columns provide the amount identifying as Latinx and the corresponding percent by neighborhood. Rows are sorted high to low according to values in the race Percent (%) column and colors (dark to light) indicate high to low values in that column.

From the data on the amount of people of color by neighborhood, it is clear that Dixwell has a disproportionate amount, at 86.5% (Table 6). The city of New Haven is 56.6% non-white, so this means The Hill and Dwight also have a disproportionately high amount of people of color. The Hill and Fair Haven both had higher portions of Latinx individuals than the city average of 31.2%, with 38.7% and 53% respectively. These numbers are important to note since The Hill, Dixwell, and Fair Haven were all redlined areas. East Rock has the lowest percentage of people of color, at 35.4%, and received an ‘A’ grade from the HOLC. A large determining factor for this drastically uneven distribution of communities of color across the city was the redlining

⁸¹ Booz Allen Hamilton Inc. “Residential Energy Efficiency in Connecticut.”

by the HOLC that deemed these neighborhoods as high risk.⁸² This is important to recognize because it influences a variety of factors beyond just racial distribution, as seen in the income data, and has implications for heat sensitivity. Dixwell and Dwight were the two warmest neighborhoods in this study-- they also have disproportionately high percentages of people of color. This data can help inform adaptation efforts in that it points to sensitive areas and highlights institutional racism that has yet to be amended.

⁸² Nelson et al. "Mapping inequality: Redlining in New Deal America."

Vulnerability

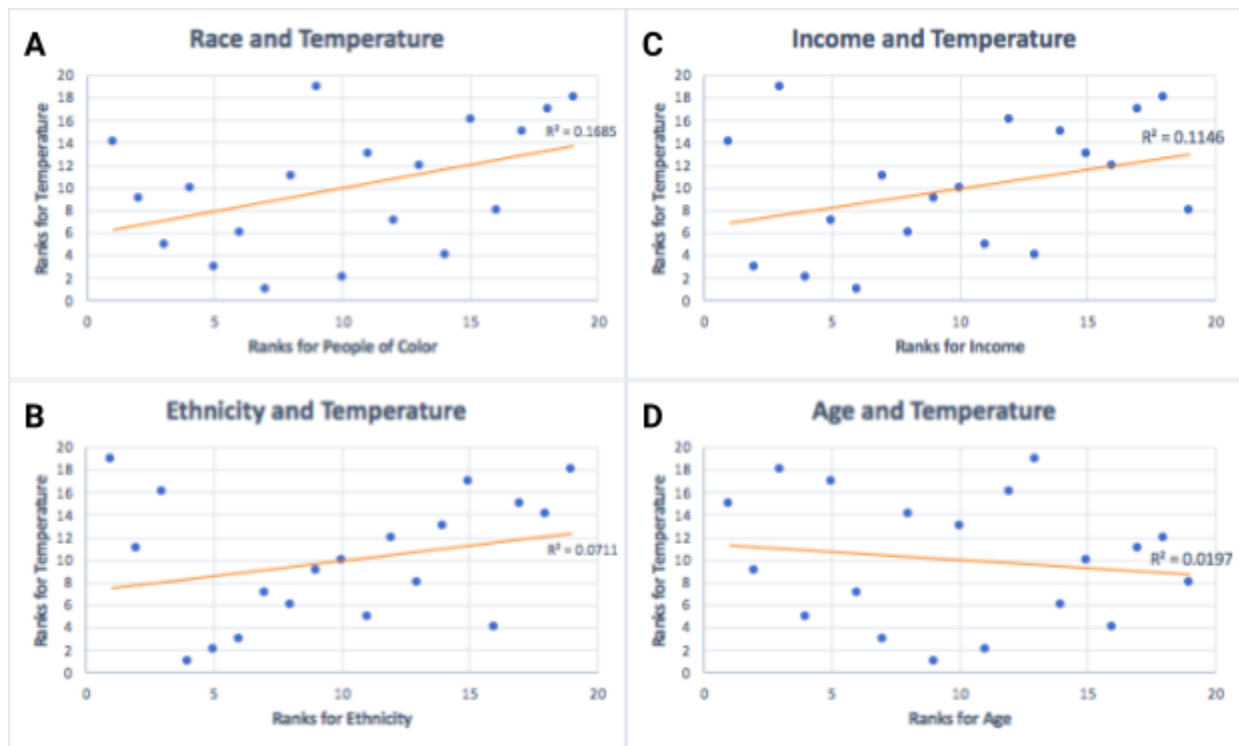


Figure 15. Spearman correlation charts for sensitivity factors and temperature. For all charts, both axis values indicate rank, so a larger value represents a lower rank and value for that variable. A) Showing the scatter plot, trendline, and r^2 values for race and temperature. B) Showing the scatter plot, trendline, and r^2 values for ethnicity and temperature. C) Showing the scatter plot, trendline, and r^2 values for income and temperature. D) Showing the scatter plot, trendline, and r^2 values for age and temperature.

A Spearman's correlation was run to determine the relationship between 19 race and temperature values at the census tract level. There was no statistically significant correlation between race and temperature ($r_s = .41$, $n = 19$, $p > .05$). The same correlation analysis was run for ethnicity, income, and age with temperature. There was no statistically significant correlation between ethnicity and temperature ($r_s = .27$, $n = 19$, $p > .05$). There was no statistically significant correlation between income and temperature ($r_s = .34$, $n = 19$, $p > .05$). There was no statistically significant correlation between age and temperature ($r_s = -0.14$, $n = 19$, $p > .05$). The

scatter plots and trendlines for these analyses can be seen in Figure 15. The lack of statistical significance could be the result of having a low n value.

Despite the lack of statistical significance, it is clear that there is still a relationship between temperature and most of the variables. The only exception being age, since the r_s value was so weak. Ethnicity and temperature also had a relatively weak correlation, largely due to the fact that Fair Haven is the coolest neighborhood and has the largest Latinx population. Without Fair Haven, there would be a stronger relationship between temperature and ethnicity. It is also important to note that Fair Haven would likely be much warmer, since it has low tree cover and high impervious surface coverage, if not for its proximity to water. The relationship between income and temperature is also skewed by the top ranking income tract in Dixwell having a temperature value in one census tract that was over two times lower than the value in Dixwell's other census tract. Here, we see a drawback of the census tract scale which only allows for an n value of 19. Race stood out, with a moderate rather than weak correlation of $r_s = 0.41$, indicating there is a positive relationship between race and temperature.

Exposure and Sensitivity Summary Table

Neighborhood	Median Anomaly (°F)	Average Tree Cover (%)	Water Area (m ²)	People of Color (%)	Latinx (%)	Poverty (%)	At-risk Age (%)
The Hill	0.75	23	528,871	58.9	38.7	35.1	3.1
Dixwell	-0.11	28	0	86.5	13.6	37.9	10.3
Dwight	-0.15	23	0	75.2	25.9	30.6	9.7
East Rock	-0.31	43	34,505	35.4	11.6	15.0	9.7
Fair Haven	-0.47	23	605,609	48.2	53.0	30.2	2.9

Table 7. Table of all exposure and sensitivity summary data by neighborhood. Rows are sorted high to low according to values in the Median Anomaly column. Length of the bars in colored columns correspond with a given value as compared to the highest value in that column. Longer bars represent a higher value.

To summarize all of the results concisely, Table 7 provides us with the values for median anomaly, average tree cover, water area, people of color, ethnicity, poverty, and age. With the rows sorted according to their value in the first column of median anomalies, from high to low, we can see trends in the other columns that correspond.

The two environmental factors included, tree cover and water area, don't show a strong corresponding relationship, but other forms of analysis substantiated that tree cover and water play a role in lowering temperatures. The areas with the highest tree cover (East Rock, Dixwell) have negative median anomalies, indicating cooler than city average temperatures, so this aligns with what was expected. With The Hill serving as an exception, the other areas with water have the coolest median anomalies.

The sensitivity factors for poverty and people of color trend well with temperature in this table. With The Hill and Fair Haven as slight exceptions, every other neighborhood ranks high to low in the same order for temperature, poverty, and people of color. The Hill is ranked highest for

temperature, and just above Dixwell, but otherwise ranks just below Dixwell in these two sensitivity factors. Dixwell's higher tree cover is what most likely influences this temperature ranking and misalignment, especially since it has lots of hot spots. Similarly Fair Haven is ranked below East Rock in the temperature column, but is otherwise just above it in the two sensitivity categories. Fair Haven's proximity to a large amount of water is the most likely influence on its lower-than-expected temperature ranking.

As for age and ethnicity, there does not appear to be much of a relationship with temperature, which is good for heat vulnerability. The warmest neighborhood has the second highest percentage of Latinx people, at 38.7%, which may be some cause for concern.

Overall, with high values in temperature, people of color, and poverty, The Hill and Dixwell seem to have the highest level of heat vulnerability when both the exposure and sensitivity variables are considered. Dwight is not far behind these two, with only a 0.04°F difference in median temperature anomaly setting it behind Dixwell, and having a higher percentage of people of color than The Hill. These areas should be prioritized in adaptation and mitigation efforts.

Discussion

Seasonality

Consistent with existing literature, this autumnal temperature data revealed the most extreme hot spots in the city, which were in The Hill. The urban heat island effect is subdued during this season, meaning temperatures more closely resemble annual averages, however, warm extremes are likely to be consistent with summer temperatures and perhaps exacerbated.⁸³ Those hot spot areas indicate the urban heat island effect at work, just as it would during the hotter months, but with less extreme values. Considering The Hill had a much warmer median than any of the other neighborhoods, it is likely that summer heat intensity here would have even more extreme discrepancies. While this study does not show the urban heat island effect in the summer, when it is most extreme, it still provides an analysis of the many factors influencing temperature and lays the groundwork for future investigation of the New Haven's urban heat landscape.

Since temperature anomalies may be more extreme in the summer, a correlation analysis between summer anomalies and the sensitivity factors may result in different correlation results, even with the same *n* value. For example, when sampled in the summer The Hill would likely have stronger temperature anomalies per census tract and since it has a high people of color percentage, this would influence the strength of the correlation. If the data showed sweeping increases for all neighborhoods, this would be even more likely, especially since most of the sensitivity factors had some relationship with temperature.

The temperature anomaly values were calculated using data from Tweed airport, the local weather station, and the results show that every neighborhood had an anomalous

⁸³ Yao Yuan et al. "Seasonal variations of the urban thermal environment effect in a tropical coastal city."; Chen, Zhang, and Zhu. "High-Resolution Simulations of the Urban Thermal Climate in Suzhou City, China."

relationship with this data. While some were quite small, The Hill had a median anomaly nearly a degree warmer than the values from Tweed. Considering these were autumnal temperature values and bound to be less extreme, in summer months these anomalies could be much larger. The anomaly range in this autumnal data set was between 4°F and -4°F. This raises an important climate communication issue for the city. Since Tweed is the local weather station, most people in the city are being informed about weather by this data, however, this study shows that there is far more variance by neighborhood. In extreme weather events, this miscommunication of accurate temperature readings could put sensitive individuals at an even higher risk. Setting up temperature sensors throughout the city to provide citizens with more accurate weather readings according to their location within the city would set people up to be more prepared for extreme heat events in their area.

Conclusions

My hypothesis that higher heat exposure would be recorded in areas with low tree cover, high impervious surface coverage, and no water proximity was upheld with The Hill as the warmest neighborhood. The Hill has the lowest observed tree cover (23%, along with Dwight and Fair Haven). While The Hill does have some water proximity, several of its census tracts are not near water and have higher heat exposure than those that do. Dixwell as the second warmest neighborhood further supports my hypothesis because it has only 28% tree cover (max observed is 43% in East Rock) and no water proximity. The only neighborhoods that are cooler than Dixwell but have higher tree coverage are Dwight and Fair Haven. However, Fair Haven is strongly influenced by water proximity and Dwight is the smallest transect so there is less variation in temperature overall here. The Hill and Dixwell neighborhoods should be prioritized in heat mitigation efforts in New Haven, especially regarding ways to improve tree cover.

Several unexpected results were recorded from this analysis, including the occurrence of more extreme hot spots in Dixwell and East Rock than in The Hill, which has a higher median anomaly. This is likely due to nuanced changes in land cover. Since these two areas have the highest tree cover, the areas within them without trees could be the hot spots. These extreme recordings are important to note for mitigation efforts.

My hypothesis that higher heat exposure would occur in areas that are predominantly minority and low income—as seen in above average percentages of people of color and people in poverty—was not supported statistically. Perhaps with a larger data set or in a different season this would be observed, since the literature that supports this expectation is largely centered around summer temperatures. The results for The Hill, Dixwell, and Dwight indicate that this relationship is positive, just weak. Each of these three neighborhoods have above average values for the percentage of people of color and people in poverty. They are also the top three warmest neighborhoods and have a majority of all hot spots in the city. Thus, since low-income areas and communities of color already suffer more negative health outcomes and are at higher risk of heat related illness, this relationship should be taken seriously, despite its lack of statistical significance.⁸⁴

Next for New Haven

Further investigation of temperature differences in the summer is necessary in order to truly understand the full extent of the urban heat island effect and how climate change will impact New Haven. Moreover, developing anomalies from data for the mean temperature *within* the city would provide a more clear picture of the variance between neighborhoods at a given time. Increasing the amount of data collected in the city, perhaps making the transects longer and more thorough in a given neighborhood, would make the data more robust. This could also

⁸⁴ Bassett and Galea. “Reparations as a Public Health Priority—A Strategy for Ending Black–White Health Disparities.”; Bailes and Reeves. “Prevention of Heat-Related Illness.”

potentially allow for a similar analysis at the census block level, which is smaller than census tract. This would increase the n value and make for a better correlation model. Extending the surveyed area of the city would also provide a more complete understanding of heat, since only 60% of New Haven's total population was included in this study. The remaining population is likely concentrated in Westville and in census tracts that are considered part of the five neighborhoods studied here, but were not within the range of my bike transects. Expanding the scope would also provide a more complete picture of the disparities across the city, since many of the areas not included are predominantly white and have higher income.

For this study, tree cover percentages were only accessible at the neighborhood level. Further investigation of NLCD data for impervious surfaces and tree cover could allow for a more robust understanding of their influence on temperature. The role of New Haven's unique built environment in developing the urban heat island effect must be understood better for well-informed mitigation efforts to be developed. In areas like Dixwell, The Hill, and Dwight, where there are lots of hot spots, knowing whether tree cover or impervious surfaces influences temperature more could directly impact the mitigation of those hot spots, which were as much as 4°F warmer than the city average. These factors have been shown to be at the root of heat exposure, and since it is expected to only get worse, it is critical that we understand them.

While data availability limited the energy analysis in this paper, research should be done to explore cooling insecurity, housing insulation and quality, and energy burdens on a more localized level. New Haven has a transportation and housing burden that is above the affordable threshold.⁸⁵ This information can serve as indicators of obstacles to adapting in high heat scenarios, for example if someone has low housing quality or transportation barriers that prevent them from seeking air conditioned shelter. A more nuanced understanding of the energy

⁸⁵ Justine Sears and Leslie Badger, "Mapping Household Energy & Transportation Affordability in Connecticut" (*Connecticut Green Bank*, October 2020).

relationships and other influential factors, at the neighborhood level, would allow for a more comprehensive development of adaptation and mitigation efforts throughout the city. For example, energy data paired with heat vulnerability data could inform an expansion of access to efficient central air conditioning for the most vulnerable populations.

With housing as the base of the Census data used in this paper, a crucial subset of the population is left out. Unhoused members of the New Haven community are more likely to suffer an extreme vulnerability to heat given their lack of shelter and resources. Researching the potential impacts of heat stress events on the unhoused population in the city would be a significant addition to ameliorating negative health outcomes related to heat. Additionally, undocumented residents may not appear in the Census, which limits the extent or accuracy of income and racial or ethnic vulnerability in some neighborhoods. This is another data gap that should be filled to fully pursue environmental justice and protect the most vulnerable.

Overall, more data is always better. Collecting this additional information and conducting additional analyses would allow for greater confidence that the observed trends are upheld and fill in the gaps. The urban heat island effect is a place-based phenomenon that is unique to every city, so a greater understanding of New Haven's climate reality requires this intimate investigation of its environmental and social characteristics. There is great potential for saving lives and making the city even more beautiful and healthy with this data, so it can't stop here.

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